Over Thirty Years Reporting on NASA's Earth Science Program

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The Editor's Corner

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The dawn of a new year is always a time for hopefulness. The rollout of multiple vaccines, starting in late 2020, gives optimism that the restrictions necessitated by COVID-19 may start to ease later in 2021. We will soon mark a year since in-person gatherings ceased. Nevertheless, as is evident from the feature and meeting summary reports in this issue of *The Earth Observer*, the NASA Earth Science community has quickly adapted to conducting its business virtually. This Editorial highlights how several specific missions and programs are continuing to persevere despite the challenges of the past year.

In the last issue we reported on the successful November launch of the Sentinel-6 Michael Freilich mission and of the first data returns from its altimeter in December.[1] Since then the spacecraft has been moved into the reference altimetry orbit. This is the same orbit that has been occupied by all of its ocean altimetry predecessors, beginning with TOPEX/Poseidon in 1992, and subsequently Jason-1, Jason-2, and Jason-3. The Sentinel-6 Michael Freilich spacecraft is now trailing Jason-3 by about 30 seconds, allowing data from the two satellites to be compared. Engineering checks on the data are almost complete and the first data will be released to the Sentinel-6 Validation Team (S6VT)[2] in the next month. So far, the data look promising and the wider science community can look forward to the first public data release later this year.

[1] See the Editorial of the November–December issue of *The Earth Observer* [**Volume 32, Issue 6**, p.1].
[2] The S6VT brings together experts from around the world in mission validation activities to provide independent validation evidence, experimental data, and advice for Sentinel-6 Michael Freilich operations. Learn more about the activities of the S6VT at *s6vt.org*.

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This photo, taken in January 2021, shows the integrated Landsat 9 observatory in a cleanroom at the Northrop Grumman facility in Gilbert, AZ, prior to acoustics testing. The two instruments, OLI-2 and TIRS-2 were previously integrated onto the spacecraft bus and are located at the top of the observatory, under a shroud designed to protect them from contamination. **Photo credit:** NASA/Northrop Grumman

In This Issue

Reminder: To view newsletter images in color, visit *eospso.nasa.gov/earth-observer-archive.*

With regard to other long-term efforts, the NASA–USGS Landsat Program has achieved nearly five decades of continuous operations. Both of the missions currently in orbit (Landsat 7 and 8) continue to operate successfully, acquiring global land imagery at 30-m resolution every eight days to support land management and monitor environmental changes. Landsat 8 experienced safe hold events in December 2019 and November 2020, but the Flight Operations Team recovered quickly with no adverse impacts. Landsat 7 is nearing its end of life (based on fuel availability) and will cease to provide scientifically usable data in late 2021. USGS has moved to a collection-based data processing approach and new surface reflectance and temperature standard products are now available via Collection 2. At the same time, the scientific community continues to find innovative uses for the archive, including large-scale, ice-velocity mapping for Antarctica, global deforestation products, and improved estimates of cropland water consumption via monitoring evapotranspiration.

Landsat 9, a near copy of Landsat 8,[3] is currently being readied for a planned September 2021 launch. This will ensure the continuity of eight-day global coverage after Landsat 7 ceases operations. The Operational Land Imager 2 (OLI-2) and Thermal Infrared Sensor (TIRS-2) instruments have been integrated on the spacecraft, and the entire observatory is undergoing environmental and performance testing at the Northrop Grumman Space Systems facility in Gilbert, AZ [see cover photo].

The NASA–USGS Landsat Science Team (LST) is responsible for providing guidance for Landsat. The LST holds periodic meetings that provide a public forum for discussing the state and future of the Landsat mission. These typically occur in winter and summer. While the February 2020 meeting was in person, the LST moved to online monthly topical meetings starting in August. Turn to page 10 of this issue to learn more about the activities of the LST Team during 2020.

As the LST looks further into the future, its members have begun to envision a new mission that will be quite different than its predecessors. Initial planning for a Landsat 9 follow-on mission (dubbed "Landsat Next") is underway between NASA and USGS. A Request for Information (RFI) was recently issued. The RFI included draft requirements that would substantially improve the science quality of Landsat data, including higher spatial resolution, additional spectral bands, and more-frequent observations. While the final mission architecture will not be decided until the end of 2021, the future of the Landsat data stream appears positive.

Related to the LST is NASA's Land-Cover and Land-Use Change (LCLUC) Science Team. The LCLUC Program focuses on the role of land use in global and climate change research. At the agency and interagency

[3] The differences between Landsat 8 and Landsat 9 are that the TIRS-2 instrument underwent an optical redesign to limit stray light and the electronics were made redundant to bring the instrument to *Class B*, as defined by *NASA Procedural Requirements* viewable at *nodis3.gsfc.nasa.gov/npg_img/N_PR_8705_0004_/N_PR_8705_0004__AppendixB.pdf.*

level, the LCLUC Program is positioned to partner with other NASA programs and agencies on climate vulnerability, impacts, and adaptation, as opportunities allow.

The LCLUC Science Team also met virtually in October 2020. The meeting provided an opportunity for LCLUC researchers from around the world to give updates on their research, network to strengthen partnerships and collaborations, highlight ongoing LCLUC issues of common interest, and address community concerns. The three days of online activities included program updates, three invited presentations from NASA Headquarters, updates from the international Multi-Source Land Imaging (MuSLI) program and the South/Southeast Asia Research Initiative (SARI), discussion on activities of the international Global Observations of Forest Cover and Land-use Dynamics (GOFC–GOLD) program, and reports from new LCLUC investigators. The 2020 meeting was dedicated to its founding program manager, Anthony "Tony" Janetos, who passed away on August 6, 2019—see *In Memoriam: Anthony "Tony" Janetos* on page 22 of this issue. This year (2021) will mark the twenty-fifth anniversary of the LCLUC STM. Look for more coverage of this quarter-century milestone in a future issue of *The Earth Observer*. Turn to page 21 of this issue to learn more about the 2020 LCLUC Science Team Meeting.

The twin GRACE Follow-On (FO) satellites, launched in May 2018, are nearing their third anniversary of measuring month-to-month gravity and associated mass changes. The overall science operations and instrument system performance have been stable throughout 2020. In addition to the baseline Microwave Interferometer (MWI) measurements, the experimental Laser Ranging Instrument (LRI) has been continuously and successfully operated in parallel. The LRI can measure inter-satellite range changes down to nanometer scales—more than an order of magnitude better than the MWI.

As of January 2021, the mission's science data teams have provided 28 global monthly maps that track Earth's dynamic surface mass movement, e.g., ice melt in Greenland and Antarctica, and land water storage changes. A major emphasis in the data processing is being placed on ensuring consistency in the climate data record between the original GRACE mission (2002–2017) and its successor. The efforts have focused on refining data calibrations to improve the science data quality. To that end, the original GRACE data record is also undergoing a final reprocessing campaign using consistent conventions and calibrations between the two missions and their respective science data systems. The release of the final GRACE data campaign is targeted for fall of 2021. In the meantime, GRACE-FO extends the mass change data record to nearly two decades, providing a unique integrated global view of how Earth's surface mass distribution and water cycle are evolving.

The GRACE and GRACE–FO Science Team also held a virtual meeting in October 2020 during which these and other items related to GRACE-FO were discussed in detail. Please turn to page 14 to learn more about this meeting.

Last but not least, for many years NASA has participated in the American Geophysical Union (AGU) Fall Meeting. Despite the pandemic, this year was no exception. Like so many other meetings and events over the past year, out of necessity the AGU had to adopt an exclusively online format. Undeterred, NASA and researchers from around the world met virtually from December 1–17, 2020.

As they do for in-person AGU Meetings, the Science Support Office coordinated NASA's exhibit presence. The virtual exhibit featured a Science Theater consisting of 75 presentations hosted on *YouTube*, live daily chats, the 2021 NASA Science calendar (available in English and Spanish), and a wide variety of resources from across the Science Mission Directorate (including Earth Science, Planetary Science, Heliophysics, Astrophysics, Biological & Physical Sciences,[4] and Science Activation). Many thanks to those from across the agency who contributed to the success of the virtual Fall AGU exhibit. Please see the article on page 4 of this issue for further information. ■

[4] Biological & Physical Sciences was added as the SMD's fifth Division in July 2020. It had formerly been part of NASA's Human Exploration Organization Directorate, where it had been known as the Space Life and Physical Sciences Research and Applications (SLPSRA) Division. Learn more about this move at *science.nasa.gov/science-news/bps/a-new-home-for-nasa-s-biological-and-physical-sciences-research*.

List of Undefined Acronyms Used in Editorial and/or Table of Contents

AGU	American Geophysical Union
GRACE	Gravity Recovery and Climate Experiment
TOPEX	Ocean Topography Experiment
USGS	U.S. Geological Survey

NASA Science at the First Virtual AGU Fall Meeting

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*The first-ever 100% virtual AGU Fall Meeting, with the tagline **Online Everywhere**, took place December 1–17, 2020.*

Introduction

It is now a familiar routine for NASA's Science Support Office to end the year coordinating the NASA Science exhibit at the AGU Fall Meeting, held in December each year. Over the years, hundreds of NASA exhibit team members, scientists, engineers, and outreach personnel have shared new research results, demonstrated the latest data technologies and tools, and told visually compelling science stories in front of NASA's Hyperwall[1] at the exhibit. Thousands from the more than 20,000 AGU Fall Meeting attendees find their way to the NASA Science exhibit each year. But 2020 had different plans in store for everyone, bringing a screeching halt to in-person scientific conferences and events, and hurling the NASA Science exhibit team into new territory: virtual events.

The first-ever 100% virtual AGU Fall Meeting, with the tagline *Online Everywhere*, took place December 1–17, 2020. NASA Science was among 68 exhibitors in the virtual Exhibit Hall. In an effort to extend the reach of this event, this article provides screenshots and associated links that visually represent the NASA Science exhibit at the first virtual AGU Fall Meeting.

Virtual NASA Science Exhibit

The virtual NASA Science exhibit featured a Science Theater, which included 77 prerecorded presentations, live daily chat times, the 2021 NASA Science calendar, and 10 navigational tabs—see **Figure 1**. Attendees clicked through the navigational tabs to explore different "areas" of the exhibit, including a Welcome graphic (shown in Figure 1),

[1] NASA's Hyperwall is a video wall capable of displaying multiple high-definition data visualizations and/or images simultaneously across an arrangement of screens. To view the full library of Hyperwall visualizations and stories, visit *https://svs.gsfc.nasa.gov/hw*.

Figure 1. This screenshot shows a visual representation of the NASA Science exhibit on the virtual AGU Fall Meeting platform. The exhibit featured the NASA logo and short exhibit description [*top left*], virtual lobby image [*top right*], a list of NASA exhibit staff members and guests online [*bottom left-hand margin*], 10 navigational tabs [*right-hand margin*], a Welcome graphic [*bottom image*], and Group Chat [*bottom*]. **Image credit:** NASA

a Science Theater presentation list, Chat Schedule, six different exhibit pages (Earth Science, Planetary Science, Heliophysics, Astrophysics, Biological & Physical Sciences, and Science Activation), and a collection of downloadable Resources. There were 36 documents and links in the Resources tab, readily available for attendees to download to their virtual briefcase (a tool often built into online conference platforms that allows attendees to collect digital media in one spot).

The NASA exhibit had 26 staff members who helped monitor the NASA Group Chat during the conference, including heavily staffed, live chat times during the week of December 7–11, 2020—see **Figure 2**. Outside of live chat times, attendees could submit questions 24/7 using the NASA Group Chat function and receive a response within 24 hours.

The NASA exhibit had 26 staff members who helped monitor the NASA Group Chat during the conference, including heavily staffed, live chat times during the week of December 7–11, 2020.

Figure 2. Chat Schedule graphic. **Image credit:** NASA

Each year, the NASA Science Calendar is a popular item at the NASA exhibit. This year was no exception—see **Figure 3**. Attendees visiting the booth could send chat messages asking how to obtain a copy of the 2021 calendar. A hardcopy calendar giveaway took place on December 7, from 6:00 – 7:00 PM ET and December 11, 6:00 – 8:00 PM ET. During these times, attendees could fill out a calendar request form to receive a hardcopy (available to U.S. residents only due to high shipping costs). The booth also promoted unlimited downloads of the calendar, available in English at *https://go.nasa.gov/3ss1upa* and Spanish at *https://go.nasa.gov/3qpF8D2*.[2] While this year's Fall AGU meeting did not feature the usual mad dash to the NASA exhibit nor the long lines of eager attendees waiting to receive their coveted copy of the NASA calendar, attendees still shared their excitement and praise via the NASA Group Chat for the collection of images, captions, and inspiring messages throughout the calendar.

Figure 3. The 2021 NASA Science calendar promotion. **Image credit:** NASA

NASA Science Theater

In a typical year, AGU attendees crowd around the NASA Hyperwall to view visually compelling images and visualizations, listen to live presentations, and participate in question-and-answer discussions. In the spirit of traditional Hyperwall talks, presenters submitted pre-recorded talks that were then hosted on a YouTube playlist

[2] The calendar is also available through the U.S. Government Publishing Office at *https://bookstore.gpo.gov/products/2021-explore-science*.

for attendees to watch at their leisure. While the in-person conference experience cannot be duplicated, one positive aspect is that all 77 talks are now available to the public and can be viewed at any time at *https://go.nasa.gov/38MQf2X*. The same list of presentations organized by topic, including presenter names and presentation titles, is also available at *https://go.nasa.gov/3nMRnb1*. Some videos have reached upward of 500 views.

While the in-person conference experience cannot be duplicated, one positive aspect is that all 77 talks are now available to the public and can be viewed at any time.

The Science Theater included six presentations submitted by winners of the *2020 AGU Michael H. Freilich Student Visualization Competition*—a contest open to undergraduate and graduate students that focuses on innovation and creativity in presenting data to a wider audience in new, more easily accessible ways—see **Table**. Having just completed its fifth year in 2020, the competition[3] has grown in popularity among AGU student attendees and the submission quality has improved greatly each year. Outside the NASA Science exhibit, these six presentations were prominently featured in the AGU Student and Early Career Scientist Lounge.

[3] For more information about the competition, visit *https://go.nasa.gov/3qgHAvw*.

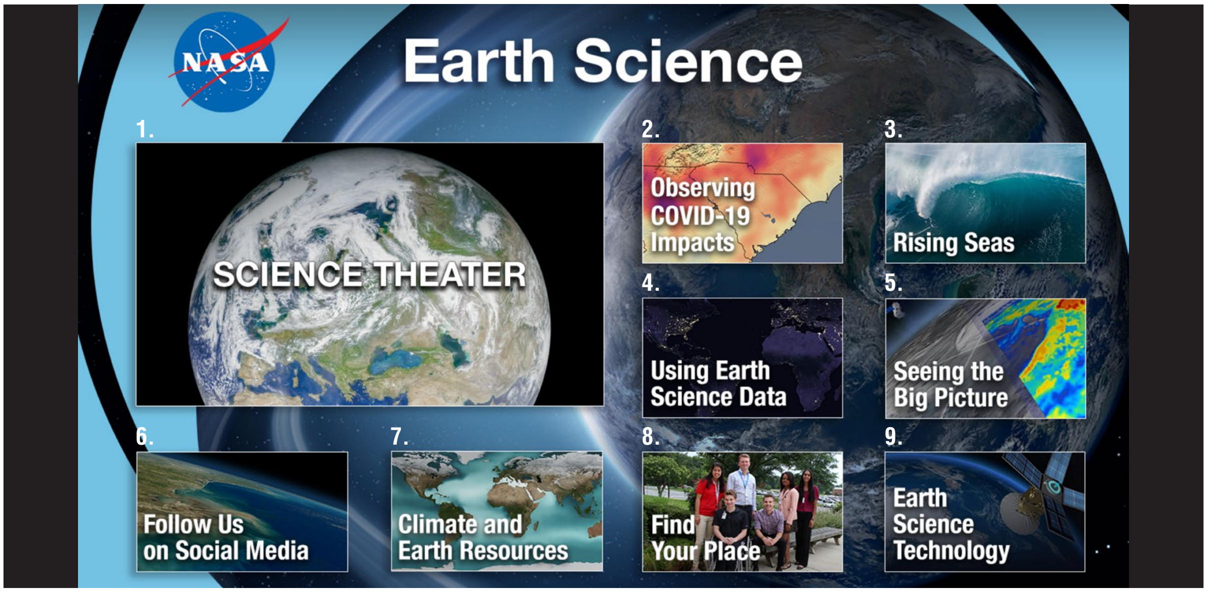
Table. Presentations by winners of the 2020 AGU Michael H. Freilich Student Visualization Competition.

Name	Organization	Winner Type	Presentation Title	Link
Brandi Downs	The Ohio State University	Grand Prize	Mapping the Annual Variation of Inland Water with GPS	*https://youtu.be/gbo63Jmy8aQ*
Jamie Callejon Hierro	University of Maryland, College Park	Grand Prize	Flux Rope Visualization	*https://youtu.be/CS4MdzPk7Gg*
Daniel O'Hara	University of Oregon	Grand Prize	Explorations in Volcanic Edifice Visualization	*https://youtu.be/BaY0RJuSqA0*
Michael Sautter	Johns Hopkins University	Grand Prize	Exploring the Deep Sea with Free and Open-Source Data	*https://youtu.be/kLrbheb8DwA*
Richard Thaxton	University of Arizona	Grand Prize	Dendrochronology in Motion: Visualizing Cottonwood Tree Growth Across Space and Time	*https://youtu.be/r2WnzR5ooKE*
Adam Chmurzynski	Dartmouth College	Runner-Up	Visualizing Biodiversity Dynamics with Forecasts of Plant Species Range Shifts	*https://youtu.be/cVTtZN1E-8Y*

NASA Science Exhibit Pages

The NASA Science exhibit featured six individual exhibit pages, shown here with associated links—see **Figures 4–9**. Each exhibit page, hosted via Google Slides, featured clickable graphics that led to secondary webpages, curated by their respective NASA Science Mission Directorate outreach communities: Earth Science, Planetary Science, Heliophysics, Astrophysics, Biological & Physical Sciences, and Science Activation. Similar to the Science Theater, the exhibit pages are open to the public and can be explored at any time.

Figure 4. Depiction of the Earth Science exhibit page. To explore the interactive page, visit *https://go.nasa.gov/39DEHhp*.



1. Science Theater *https://go.nasa.gov/3nOnlDQ*
2. Observing COVID-19 Impacts *https://go.nasa.gov/2M8repN*
3. Rising Seas *https://go.nasa.gov/3isBjKp*
4. Using Earth Science Data *https://go.nasa.gov/3irgRcU*
5. Seeing the Big Picture *https://go.nasa.gov/2M56Ypj*
6. Follow Us on Social Media *https://go.nasa.gov/2LYRwed*
7. Climate and Earth Resources *https://go.nasa.gov/3nZwJ7u*
8. Find Your Place *https://go.nasa.gov/2Kr6J7k*
9. Earth Science Technology *https://go.nasa.gov/2XWC1Gi*

Figure 5. Depiction of the Planetary Science exhibit page. To explore the interactive page, visit *https://go.nasa.gov/3qAVEAg*.

1. Science Theater *https://go.nasa.gov/3bUyYa4*
2. Other Missions and Programs *https://go.nasa.gov/3ip0LAA*
3. Countdown to Mars *https://go.nasa.gov/3oYIs7T*
4. Data Visualization Tools *https://go.nasa.gov/3bUuNe4*
5. Career Paths *https://go.nasa.gov/3oZJlNo*
6. Social Media *https://go.nasa.gov/3iqDtu9*
7. Virtual Swag *https://go.nasa.gov/3sERZTF*
8. Year of the Asteroids *https://go.nasa.gov/2XVi4z*

Figure 6. Depiction of the Heliophysics exhibit page. To explore the interactive page, visit *https://go.nasa.gov/3o2P1Vw*.

1. Heliophysics Missions *https://go.nasa.gov/3pcgQMJ*
2. Science Theater *https://go.nasa.gov/38Vvouj*
3. Early- to Mid-Career Scientists *https://go.nasa.gov/3nXgEPN*
4. Heliophysics @ NASA *https://go.nasa.gov/3qF2pB3*
5. Follow Us Everywhere Under the Sun *https://go.nasa.gov/3nYsyJh*
6. For Learners *https://go.nasa.gov/3sEiDMl*

Figure 7. Depiction of the Astrophysics exhibit page. To explore the interactive page, visit *https://go.nasa.gov/3o5zx3i*.

1. James Webb Space Telescope *https://go.nasa.gov/2XSty6X*
2. Science Theater *https://go.nasa.gov/2XUuhES*
3. Data *https://go.nasa.gov/3iE6O4x*
4. Missions *https://go.nasa.gov/2XSZpo2*
5. Social Media *https://go.nasa.gov/2XWPDkQ*
6. For Learners *https://go.nasa.gov/38UCjUy*

Figure 8. Depiction of the Biological & Physical Sciences exhibit page. To explore the interactive page, visit *https://go.nasa.gov/3sNgTAP*.

1. Space Biology
   https://go.nasa.gov/39J9PMQ
2. Science Theater
   https://go.nasa.gov/3bR5V7a
3. Physical Sciences
   https://go.nasa.gov/3bUFHAA
4. Connect with Biological and Physical Sciences
   https://go.nasa.gov/3sFv1Mg
5. Biological & Physical Sciences 2023-2032 Decadal Survey
   https://go.nasa.gov/34QCmy
6. Find Your Place
   https://go.nasa.gov/2Ngo6c5

Figure 9. Depiction of the Science Activation exhibit page. To explore the interactive page, visit *https://go.nasa.gov/35Xo0g4*.

1. Tools for Learning
   https://go.nasa.gov/39Opf2f
2. Science Theater
   https://go.nasa.gov/3sKp5Bx
3. Access Data
   https://go.nasa.gov/2NpVT2R
4. Citizen Science
   https://go.nasa.gov/39MWMtM
5. Science Activation Teams
   https://go.nasa.gov/34leYWA
6. Dissemination Networks
   https://go.nasa.gov/3bX61tO

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An Update on the 2020 Activities of the Landsat Science Team

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Christopher Crawford, U.S. Geological Survey, Earth Resources Observation and Science Center, cjcrawford@usgs.gov

Introduction

Landsat satellites have been collecting imagery of Earth's land areas continuously since 1972, and the utility of the archive for science continues to grow. At present, two satellites are operational (Landsat 7 and Landsat 8), with Landsat 9 under development.[1] The U.S. Geological Survey (USGS)/NASA Landsat Science Team (LST) held its winter meeting February 4–6, 2020, in Phoenix, AZ, to discuss the USGS data products strategy, the status of the upcoming Landsat 9 mission, and requirements for future land-imaging missions—see **Photo** below.

During the meeting, LST members had the opportunity to visit the Northrop Grumman Space Systems assembly facility in Gilbert, AZ, and see the Landsat 9 spacecraft being built. At the time of the visit, both the Operational Land Imager 2 (OLI-2) and Thermal Infrared Sensor 2 (TIRS-2) had been mechanically integrated onto the spacecraft bus. The Northrop team also led a tour of their integration and test facilities, including clean rooms and environmental test facilities.

The LST had made plans for a summer meeting in Madison, WI; however, the COVID-19 pandemic brought an abrupt end to in-person gatherings in March 2020, which forced the LST to move to online meetings for the foreseeable future. Therefore, the LST had to adjust its meeting strategy to accommodate the new virtual-meeting realm the world suddenly had entered. Beginning in August, and every month since, the LST has held monthly online topical meetings, two-to-three hours in length.

This article summarizes the main discussions of the February meeting, as well as highlights from the subsequent monthly meetings held in 2020. The full agenda and meeting presentations can be found at *https://www.usgs.gov/core-science-systems/nli/landsat/landsat-science-team-meeting-february-4-6-2020*.

February Meeting

C.J. Loria [USGS Earth Resources Observation and Science (EROS) Center—*Director*] and **Peter Doucette** [USGS National Land Imaging (NLI) Program] gave opening remarks on the status of land science within USGS. Loria noted the burgeoning interest in improved spatial resolution and spectral information for future Landsat missions, and how land remote sensing data could support the EarthMap[2] concept of integrated geospatial information. Doucette discussed priorities within the USGS's NLI Program, including operational continuity for Landsat 8 and 9; development

[1] To read much more about Landsat's history and highlights from the first 20 years of Landsat 7, see "The Living Legacy of Landsat 7: Still Going Strong After 20 Years in Orbit" in the July–August 2019 issue of *The Earth Observer* [**Volume 31**, **Issue 4**, pp.4–14—*https://go.nasa.gov/390VE6w*].

[2] EarthMap is a term being used to refer to the USGS's vision for integrated Earth System information for science and decision support. To learn more, visit *https://my.usgs.gov/confluence/pages/viewpage.action?pageId=635125463*.

Photo. The USGS/NASA Landsat Science Team at the February 2020 meeting in Phoenix, AZ—the group's last in-person gathering before the COVID-19 pandemic necessitated virtual meetings. **Photo credit**: Jeff Masek of *Landsat Next*;[3] the upcoming release of Land Change Monitoring, Assessment, and Projection (LCMAP) datasets; and development of Analysis Ready Data (ARD)[4] from the Landsat archive. Doucette also noted new emphasis on the application of cloud computing and development of artificial intelligence/machine learning algorithms for land information products.

Chris Crawford [EROS] gave on overview of current EROS activities, focusing on Landsat operations and data production. USGS has moved toward a collection-based archive for Landsat data, with both Level 1 (top-of-atmosphere) and Level 2 (atmospherically corrected) image products available. Collection 2 products, featuring improved geolocation via incorporation of new ground control, are being processed during calendar year 2020. Crawford also discussed the status of Global ARD product prototyping, which would be tiled and put into a global projection for easy analysis. While the LST was generally in favor of implementing Global ARD products as soon as possible, given the processing burden required, USGS felt that further study may be needed. Crawford also discussed the December 2019 safehold event of Landsat 8. The safehold occurred during a night, off-nadir pointing event, such that the spacecraft onboard systems anticipated that a direct look at the sun could occur at the Earth's terminator. The team discussed the wisdom of permitting such off-nadir acquisitions in the future. Crawford emphasized that the flight operations team would improve planning for future off-nadir acquisitions to minimize the probability of future safehold events.

Crawford also led a discussion exploring the utility of continuing to acquire Landsat 7 images in 2021. Since Landsat 7 no longer has sufficient fuel for inclination maneuvers, its equatorial crossing time will move earlier in the morning, altering solar illumination conditions within the imagery. Images with lower sun elevation are not consistent with the historical Landsat image archive and may produce erroneous results when used for multi-date change detection. However, given delays in launching Landsat 9, the LST subsequently endorsed the continued collection of Landsat 7 data until Landsat 9 becomes operational—even if those data cannot immediately be incorporated into the archive due to the lower sun angles.

Del Jenstrom [NASA's Goddard Space Flight Center (GSFC)] and **Brian Sauer** [EROS] presented the status of Landsat 9 development.[5] Landsat 9 is a near copy[6] of Landsat 8 and will host the OLI-2 and TIRS-2 instruments. Both instruments have been delivered to Northrop Grumman Space Systems (the spacecraft vendor) and integration was underway at the time of the meeting. Sauer presented details of the Landsat 9 ground system development, which is proceeding according to schedule.

Planning for a follow-on mission for Landsat 9 is also underway. **Jeff Masek** [GSFC] discussed the outcomes of the 2019 Architecture Study Team for a Landsat Next mission. Surveys from the USGS revealed a strong desire for improved spatial resolution, more-frequent coverage, and a limited number of additional spectral bands to support new applications such as water-quality monitoring. After reviewing a set of mission concepts generated by the Architecture Study Team, NASA and the USGS subsequently endorsed a *superspectral* mission concept with 10-m (~33-ft) spatial resolution in the visible/near-infrared, 60-m (~197-ft) resolution in the thermal infrared, and some 25 spectral bands across the entire spectrum. Preformulation work on the Landsat Next concept began in April 2020 and will culminate in a Mission Confirmation Review in late 2021.

LST members **Curtis Woodcock** [Boston University], **Matthew Hansen** [University of Maryland, College Park (UMD)], **Mike Wulder** [Canadian Forest Service], and **David Roy** [Michigan State University] returned to the concept of global ARD, with a series of presentations that illustrated the science applications of having gridded, tiled reflectance datasets available. Topics included mapping wildfire burned areas, biomass dynamics of Canadian forests, and global land cover analysis—for example, see **Figure** on page 12.

Kristi Kline [EROS] gave an update on the Landsat Products Improvement Project, an effort to provide new user interface and access mechanisms to the Landsat archive. Landsat data that can be processed from the archive (except for a temporary cache of the most recently acquired images) will be migrated to the *commercial cloud*[7] for storage and distribution. Cloud-based Landsat data will be stored in Cloud Optimized GeoTIFF (COG) format to support advanced services such as subsetting and individual spectral band downloads. Product metadata will be available in a SpatioTemporal Asset Catalog (STAC) format to promote interoperability. Finally,

[3] Landsat Next is the term being used to refer to Landsat 10. As is discussed in this summary, Landsat 9 is essentially a copy of Landsat 8, both of which are similar to Landsat 7. However, the "next" Landsat is expected to differ significantly from its predecessors.

[4] To learn more about Analysis Ready Data, visit *https://www.usgs.gov/core-science-systems/nli/landsat/us-landsat-analysis-ready-data?qt-science_support_page_related_con=0#qt-science_support_page_related_con*.

[5] UPDATE: Landsat 9 was originally scheduled for launch in December 2020. However, delays with spacecraft integration and (subsequently) COVID-19 have delayed launch to September 2021.

[6] The only differences between Landsat 8 and Landsat 9 are that the TIRS-2 instrument underwent an optical redesign to limit stray light and the electronics were made redundant to bring the instrument to Class B.

[7] The commercial cloud refers to cloud computing resources that are provided by commercial vendors. Examples would be Microsoft's Azure and Amazon Web Services.

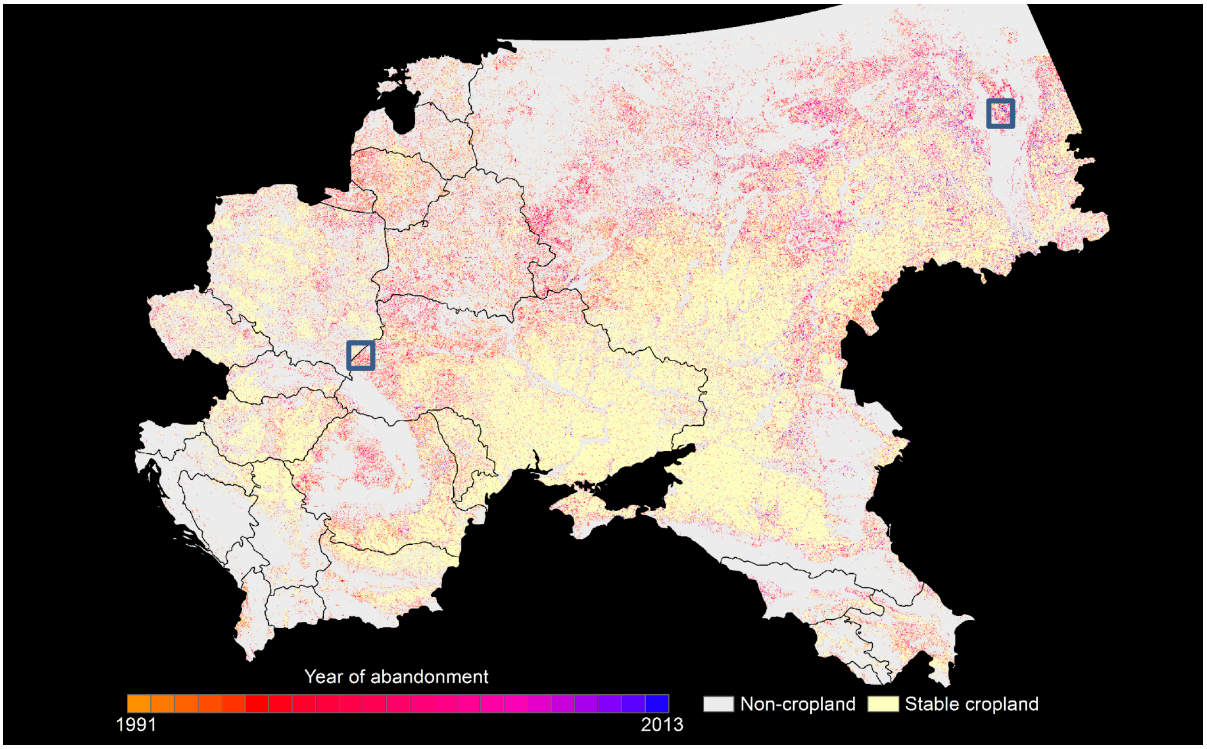

Figure. Abandonment of marginal farmland was a key part of land change in the post-Soviet era (i.e., since 1991) across Eastern Europe and Southern Russia. This map shows the distribution and year of agricultural land abandonment in these areas. It was generated by analyzing thousands of Landsat images acquired during the last 30 years. **Image credit**: **Volker Radeloff** [University of Wisconsin, Madison]

USGS is working on *LandsatLook*, a new online tool geared towards direct commercial cloud access to Landsat data (*https://landlook.usgs.gov*).

The third and final day of the meeting focused on interactions between Landsat and the European Sentinel-2 mission, the Landsat-like part of the European Copernicus satellite program for environmental monitoring. **Cody Anderson** and **Mike Choate** [both at EROS] discussed the adoption of the Sentinel-2 Global Reference Image (GRI) along with the Landsat 8 ground control dataset to improve geolocation of Collection 2 Landsat imagery and improve geospatial interoperability with the Sentinel-2 mission. **Jeff Masek** also provided an update on the Harmonized Landsat–Sentinel-2 (HLS) project (*https://go.nasa.gov/3o4BcGh*), which is providing a single surface reflectance dataset using inputs from both sensors—see example on page 24 of this issue. A new, global version of HLS is being processed by the Interagency Implementation and Advanced Concepts Team (IMPACT) at NASA's Marshall Space Flight Center and should be available from the Land Processes Distributed Active Archive Center in late 2020.

Patrick Griffiths [European Space Agency (ESA)] then presented an update on the European Copernicus program. Sentinel-2 continues to acquire excellent quality data, and new high-priority missions are moving forward within ESA, including a new Land Surface Temperature Mission (LSTM). However, Griffiths noted that due to technical limitations on the archive, access to the historical Sentinel-2 archive would be restricted to a few scenes per hour from the Copernicus OpenAccess Hub.[8] This restriction on data downloads raised concerns with the LST, and the USGS was asked to raise the issue at future bilateral meetings.

Beginning with Collection 2, the USGS has started producing standard, operational Level-2 products (surface reflectance and temperature) from Landsat, and in parallel has initiated production of selected Level-3 products for the U.S. These include surface water extent, evapotranspiration, snow cover, and aquatic reflectance. **Chris Crawford** reviewed the process of adopting and validating algorithms for higher-level products ("research to operations") and noted that active engagement of the LST was desired in introducing new algorithms and data products for transition to operational status.

August–October Meetings

The August LST meeting focused on Landsat Collection 2 processing status and the migration of the Landsat archive to USGS-contracted commercial cloud platforms. The LST brought up various concerns regarding the migration to Collection 2, including availability of lower processing level, top-of-atmosphere

[8] The Copernicus Open Access Hub (*https://scihub.copernicus.eu*; previously known as Sentinels Scientific Data Hub) provides complete, free, and open access to user products from all Sentinel missions, starting from the In-Orbit Commissioning Review (IOCR).

reflectance and apparent temperature products, the lag time associated with Level 2 processing, and the relative geolocation differences between heritage Collection 1 and new Collection 2 datasets. The team also pushed for further processing the Landsat Multispectral Scanner (MSS) archive from the 1970s and 1980s in order to extend the available record of Level-2 products for analysis.

The October LST meeting focused on Landsat Next. Following introductory remarks from **Tim Newman** [USGS—*Coordinator for National Land Imaging*] and **Peter Doucette**, **Jim Pontius** [GSFC—*Landsat Next Project Manager*] gave an overview of Landsat Next Pre-Phase A activities for 2020-21. These activities include Mission Design Studies, formulating mission requirements, and issuing a Request for Information (RFI) leading to a Mission Concept Review by the end of 2021. **Zhuoting Wu** [USGS] discussed the outcome of a series of virtual workshops held during May and June to refine the spectral band choices for the new sensor. **Jeff Masek** and **Chris Crawford** reviewed the RFI and Draft Mission Requirements. At present, the draft Landsat Next requirements specify higher spatial resolution [10–20 m (33–66 ft) in the reflective bands and 60 m in the thermal infrared] compared to past Landsat satellites, as well as additional spectral bands. The radiometric quality of Landsat Next is anticipated to be on par with the current Landsat 8 system. New orbits are being investigated that could provide more frequent (<16 day) temporal revisit. Pontius noted that a key trade for Landsat Next will be the decision whether to use a traditional single-platform architecture or a constellation of narrow-swath platforms. A constellation approach offers potential advantages, including improved temporal revisit, resiliency in case of the failure of an individual platform, and possible cost savings through constructing instruments and platforms via an "assembly line" approach. However, narrower swaths also provide smaller individual images, and some geographic context for image analysis is therefore lost.

Conclusion

LST meetings provide a public forum for discussing the state and future of the Landsat mission. After nearly 50 years of land monitoring, Landsat continues to serve as a backbone for the remote sensing science and applications communities. The multidecadal data record provides an invaluable view of the changes that have taken place across the land, cryosphere, and coastal environments, and how human activities have altered the planet's biosphere. The migration within USGS toward standard, collection-based data products has provided a structure for continuously improving the quality of Landsat data, and for introducing new biophysical and geophysical products derived from the Landsat archive.

The switch to shorter, more frequent online LST meetings during the COVID-19 pandemic has generally been successful. Future monthly team meetings will focus on further planning for Global ARD, initial planning for Collection 3 data products, U.S.–European cooperation on Landsat and Copernicus, and experiences with the Landsat Collection 2 data products. The coming year will also see an increasing focus on the upcoming launch of Landsat 9, currently scheduled for September 2021.

In addition to the monthly meetings covering LST business, **Justin Huntington** [Desert Research Institute] has set up a monthly seminar series to provide a forum for Landsat-related research updates. These seminars have covered a diverse range of topics since the summer, including the USGS surface water product, application of Landsat data to biodiversity assessments, global mapping of burned areas, application of reflectance time series to land cover change, and new approaches to atmospheric correction.

Additional information about Landsat 9 and the Landsat science mission can be found on the GSFC Landsat site (*https://landsat.gsfc.nasa.gov*). ■

NASA Science at the First Virtual AGU Fall Meeting

continued from page 9

Summary

Despite exceedingly unusual circumstances, the NASA Science exhibit community has persevered and remains committed to sharing the science that results from the myriad activities the NASA team undertakes. COVID-19 accelerated an already existing trend toward virtual events. Although different in many ways from in-person events, virtual events also offer new opportunities, including the ability to reach more people than ever before, describe data analytics, and provide creative online features (e.g., gamification and participation points). Even after life "returns to normal," it seems likely many scientific conferences and events will include a virtual component, offering a *hybrid* experience (i.e., a mix of in-person and virtual participation).

For nearly 30 years, NASA's Science Support Office has strived to provide an inspiring and interactive venue that enables a variety of audiences worldwide to connect with NASA Science. That mission remains strong, and we look forward to sharing NASA science with each of you via a variety of information transfer mechanisms. Explore with us. ■

Summary of the 2020 GRACE and GRACE Follow-On Science Team Meeting

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Introduction

The third joint Gravity Recovery and Climate Experiment (GRACE) and GRACE Follow-On (GRACE-FO) Science Team Meeting [GSTM] took place October 26–29, 2020. Due to the ongoing COVID-19 pandemic, the planned face-to-face GSTM 2020 in Potsdam, Germany, could not take place. Instead, for the first time ever, the 2020 GSTM took place as an online meeting, which was organized by the Helmholtz Centre Potsdam—GFZ German Research Centre for Geosciences.

Over 180 registered participants from 17 countries participated in the meeting—see **Photo** below—to share new results from the GRACE-FO data record, which as of December 2020 extends the 15-year GRACE data record by over 27 monthly gravity and mass change fields. The discussion of discoveries and updates covered the combined GRACE & GRACE-FO [abbreviated GRACE(-FO) hereinafter] climate data record, which now spans nearly 19 years.

To account for the challenge of different time zones, there were live video sessions in the morning and late afternoon (Central European Time). These video sessions were recorded and made available on demand for all registered participants.

There were two types of presentations: *live displays*, which were presented during video sessions, and *offline displays*, which were forums for offline discussion. These were intended to mimic poster presentations at an in-person meeting. Despite different time zones, there was good online participation for all sessions. The interactive chat capability enabled dialogue between participants to discuss results.

The videos, presentation slides, and posters are archived and accessible from *https://www.gstm-2020.eu/home.html*.

Meeting Overview

As usual, the GSTM was a mixture of moderated discussions on specific themes and contributed presentations on various subjects. The meeting opened on October 26 with a GRACE-FO Project Status session, which consisted of the mission and flight segment technical status, future science plans, and status of and information on the latest GRACE(-FO) Release 06 (RL06) data from the Science Data System. On the following three days, the meeting continued with its scientific program. Science Team members and other attendees contributed abstracts that were used to compile the following summary, which starts with an update on the status of GRACE-FO, followed by highlights from the four days of online meetings.

The complete GRACE-FO STM program, abstracts, and many of the presentations are available at *https://www.gstm-2020.eu/home.html.*

Update on GRACE-FO

The twin GRACE-FO satellites, launched on May 22, 2018, are tracking Earth's water movement and

Photo. A sign of the times. A photo of some of the GSTM participants. **Photo credit:** NASA global surface mass changes that arise from climatic, tectonic, and anthropogenic changes, and enable new insights into variations of ice sheet and glacier mass, land water storage, and changes in sea level and ocean currents—with important applications for everyday life. GRACE-FO is a U.S.–German collaboration between NASA and GFZ.

The GRACE-FO continuity mission has been providing monthly gravity and mass-change observations since June 2018. As of December 2020, the GRACE-FO project team has processed and released 27 monthly gravity fields—the most recent being from October 2020.[1] The primary mission objective for GRACE-FO is to provide continuity for the monthly GRACE mass-change observations (made from 2002 to 2017) via its Microwave Interferometer (MWI) intersatellite range-change observations. GRACE-FO also operates a novel Laser-Ranging Interferometer (LRI) as a technology demonstration for future GRACE-like missions and more-accurate satellite-to-satellite ranging observations. The mission is in its primary science operations phase, which will last five years from launch.

DAY ONE

As has been done at the last few meetings, the first day of the meeting began with opening remarks, and then presenters provided the Science Team members with a detailed assessment of the GRACE-FO mission status.

GRACE-FO and GRACE Project Status

The meeting began with opening remarks from meeting host **Frank Flechtner** [*GFZ—GRACE-FO Mission Manager,* Germany] and **Michael Watkins** [NASA/ Jet Propulsion Laboratory (JPL)—*GRACE-FO Science Lead*]. After the welcome, Felix Landerer [JPL—*GRACE-FO Project Scientist*] presented an overview of the GRACE-FO satellites and their instrument status, summarizing the performance of the main science instruments, the MWI [including global positioning systems (GPS)], accelerometers, and star cameras. Landerer highlighted that GRACE-FO continues to meet its goal of extending the GRACE record at equivalent precision and spatiotemporal sampling. The overall science instrument and flight system performance during the mission has been very stable, and monthly mass-change data have been delivered to users ahead of schedule. The mass changes observed by GRACE-FO continue to be consistent with independent mass-change estimates derived from precipitation and temperature data. This consistency, the overall GRACE-FO measurement system's performance, and independent geophysical signal assessments provide high confidence that no biases exist between the two gravity missions, despite the 11-month gap.

After the opening presentations came a series of status reports on programmatic mission operations, science operations, and science data system processing. **Krzysztof Snopek** [GFZ] reported on the ground and mission operations at the German Space Operations Center (GSOC), which is responsible for GRACE-FO spacecraft operations. **Himanshu Save** [University of Texas, Center for Space Research (CSR)] provided an overview and assessment of the science operations. **Christopher McCullough** [JPL] reviewed the status of GRACE(-FO) Level-1 (L1) reprocessing at JPL, including improvements made to the LRI L1 data processing as well as accelerometer calibrations. **Samuel Francis** [JPL] from the LRI instrument team provided a status update of the experimental LRI performance and its highly precise ranging measurements (which provide as much as 30 times more-accurate satellite-to-satellite ranging than the MWI). The on-orbit LRI experience has been very positive, with the LRI collecting science data in parallel to the MWI and operating very stably and robustly. Due to the very low noise levels even at high frequencies, the LRI data are also being used to support center-of-mass and thruster calibrations to augment the accelerometer measurements.

Representatives of the three GRACE-FO mission Science Data System (SDS) centers (JPL, GFZ, and CSR) summarized the status of the latest RL06 Level-2 (L2) gravity-field products, including an overview of background dealiasing models (GFZ), the new JPL *mascons*[2] (JPL), and new data-processing strategies [e.g., via range acceleration (CSR) and using the novel LRI ranging observations (JPL, CSR)]. The gravity-field results from the LRI measurement are consistent with the primary microwave-ranging processing and demonstrate potential for advances by exploiting the very-low noise level of the LRI measurement.

The GRACE team provided an update on the final release of GRACE data—Release 07 (RL07), which is currently in progress and slated for delivery in the fall of 2021.

DAYS TWO THROUGH FOUR

The remainder of the meeting featured eight online sessions spread over three days. There were presentations that included: analytical techniques for gravity-mission data; methods to bridge the gap between the end of science operations for GRACE and beginning science data collection with GRACE-FO, as well as future mission concepts; science analysis of mass-transport data in the fields of hydrology, oceanography,

[1] After an anomaly on one of the GRACE-FO satellites caused a brief disruption of science data collection in August and September 2018, the collection of science-quality data resumed in October 2018.

[2] A mascon, or mass concentration block is a form of gravity field basis function to which GRACE(-FO)'s inter-satellite ranging observations are fit. Learn more at *https://go.nasa.gov/2M9d2gx.*

glaciology, solid-Earth, and interdisciplinary sciences; and a discussion of GRACE and GRACE-FO applications in the broader context of NASA's Applied Sciences Program. In addition to the live presentations, offline presentations (i.e., posters) relevant to each topic were on display for chat discussion throughout the meeting.

Analysis Techniques and Intercomparisons

The Analysis Techniques and Intercomparisons session included a couple of presentations by the SDS centers, which provided more details about the processing of LRI data as well as validating both MWI- and LRI-based monthly gravity fields. Apart from using the LRI data as an observation in gravity-field estimation, these data could potentially also be used to improve the satellites' attitude products.

Several other processing centers presented their most recent efforts to process GRACE-FO gravity-field time series and showed that these time series are of comparable quality with the official SDS solutions. Many of these available solutions are already used by the Combination Service for Time-variable Gravity fields (COST-G)—a product center of the International Gravity Field Service (IGFS)—to generate improved operational combined monthly GRACE-FO gravity field solutions.

Other presentations in this session explored new science opportunities that are enabled by the LRI data, such as the validation of static gravity field models and the examination of daily to weekly time-variable gravity signals (e.g., over ocean gyres). The excellent signal-to-noise ratio of the LRI instrument also revealed that by considering the effect of ellipticity and a nonuniform seawater density when computing the ocean tide geopotential in GRACE-FO gravity field processing, ocean tide residuals can be reduced by about half. Moreover, in combination with MWI data, LRI data allow for cross-calibration of the two independent intersatellite ranging systems and can also help to separate ranging noise from other sources of noise—beneficial for a proper stochastic modeling of the GRACE-FO science instrument data.

An intercomparison study of signals and noise in the available GRACE(-FO) time series highlighted that the long-wavelength part of the gravity fields, i.e., the low-degree gravity coefficients, explains most of the discrepancies between individual time series in terms of mass balance trends of the polar ice sheets. As shown in another presentation, Satellite Laser Ranging (SLR) observations play an important role to add valuable information to GRACE(-FO) mass balance estimates at large spatial scales.

Future Gravity Missions

Future gravity mission designs and how to ensure data continuity and consistency across successive gravity measurements were discussed in this session. The 2017 NASA Earth Science Decadal Survey Report[3] highlighted mass transport monitoring through gravity change as one of five top priorities in Earth observation for the next decade, in collaboration with international partners.

The first presentation in this session examined the spatial resolution of the next generation gravity missions in two different orbital configurations, assessing polar versus inclined orbits, and discerning how the satellites' relative geometry, particularly the polar gap issue in some of the proposed satellite orbit proposals, would impact the resolution and accuracy.

Several different gravity mission concepts were examined for their feasibility and economic efficiency to provide a cost-effective alternative to the previous gravity field satellites while simultaneously increasing the space and time resolution and minimizing known error effects such as the aliasing due to under-sampling of signals and uncertainties in ocean tide models.

The French (Centre National d'Études Spatiale) MARVEL[4] mission proposal team reported that a Phase-A study was launched in January 2020. The pre-Phase-A MARVEL study, taking into account the Mass Change studies on the NASA side and European Space Agency (ESA) side, is now reoriented toward a pendulum-type orbit for the next gravity mission concept.

There was also a presentation on an alternative future gravity mission concept, named GRACE-I. The "I" stands for ICARUS, which itself is an acronym for International Cooperation for Animal Research Using Space. Developed at GFZ in Germany, this innovative scientific and technological package would place the ICARUS payload system on a GRACE-like mission (hence GRACE-I) and allow for parallel observations of changing global water resources and space-based biodiversity monitoring—a novel emerging capability with the potential to observe migratory routes of animal species.

[3] For an overview of the 2017 Earth Science Decadal Survey visit *https://science.nasa.gov/earth-science/decadal-surveys*. The full report can be accessed in several forms from *https://www.nap.edu/catalog/24938/thriving-on-our-changing-planet-a-decadal-strategy-for-earth*.

[4] MARVEL stands for Mass And Reference Variations for Earth Lookout. It is a proposal for a single mission fulfilling two major goals of geodesy: monitoring the mass transfers within the Earth system with increased precision and realization of the reference frame. Scientific objectives would include measurements of geodesy, hydrology, cryosphere, oceanography, earthquakes, clime, and post-glacier rebound—all of which are highly relevant to society.

Small satellite systems are increasingly being used in scientific missions, due to their affordability and improvement in performance over the past years.[5] A small satellite constellation of GRACE-like pairs or other inter-satellite ranging configurations could potentially allow for improved spatial and temporal resolution as well as for a high inherent system redundancy. However, the design of such a mission architecture is not straightforward, due to the many options and components that need to be considered. There was a presentation about a multi-objective evolutionary algorithm based on Darwinian theory that would help to identify future GRACE-like constellations that are optimized to retrieve sub-monthly time-varying gravity field events at the desired accuracies.

In addition to geometric considerations for future gravity missions, instrument payload and technology advances, such as the novel LRI on GRACE-FO, have the potential to improve measurement accuracy in the future. It was shown that based on idealistic point-mass sources distributed on the surface of the Earth, the minimum detectable mass change for a laser as is operated on GRACE-FO could be as low as 0.5 Gigaton.

Finally, NASA's multi-center Mass Change Designated Observable Study Team—formed in response to the 2017-2027 U.S. National Academy of Sciences Decadal Survey for Earth Science and Applications from Space—gave an update on the progress made and future plans for the Mass Change Designated Observable study. Progress includes development of a Science and Applications Traceability Matrix (SATM), definition of three different architectural classes that have potential to be responsive to the designated science objectives, and a framework to quantitatively link the performance of specific architectures to the SATM. A Value Framework has been developed to assess the value of each architecture in terms of science return, cost, schedule, and technical maturity, and results assessing the value of 50+ architecture variants were shown and discussed.

Solid Earth Sciences

As the data record from satellite time-variable gravity lengthens, slower solid-Earth processes like glacial isostatic adjustment (GIA)[6] and deep interior Earth geophysical phenomena can be examined and determined more accurately. This ongoing solid Earth uplift or sinking is contributing to the measurements of gravity change and land deformation, respectively, by GRACE(-FO) and the global positioning system (GPS). Two GSTM contributors jointly examined these complementary data records to improve contemporary GIA estimates, which are a key correction for accurate quantification of current ice mass loss over Greenland and Antarctica, as well as hydrology changes over the North American Arctic and subarctic regions.

The first presentation on GIA included a comprehensive set of GPS uplift rates for North America that is more accurate than in prior studies due to more sites and a longer data time history, removal of elastic loading produced by increases in Great Lakes water, and technical advances in GPS positioning that have significantly reduced the dispersion in position estimates. The GPS uplift rates indicate low value of the Earth's viscosity in the top 700 km (435 mi) of the lower mantle for GIA models.

The second presentation on GIA discussed a method to estimate GIA and elastic deformation by the present-day ice-mass change in the GPS time series using the example of Casey Station in East Antarctica. A high-resolution model indicated present-day ice-mass-change at the outlet of Totten Glacier from 2002 to 2017, with accelerated loss in the second half of the period. With this, the *viscoelastic deformation* attributed to GIA was estimated to contributions of 30–60% among the observed GPS vertical deformation trends.

Finally, another presentation during this session discussed how convective motions in the Earth's liquid core and associated mass redistribution might contribute to temporal variations of the gravity field, and possibly be detectable in the GRACE(-FO) data. Spatiotemporal correlations at interannual time scale between the gravity and magnetic fields measured respectively by the GRACE mission and its predecessor, the Challenging Minisatellite Payload (CHAMP), had already been reported recently. A new project, called GRACEFUL,[7] recently selected by the Synergy Program[8] of the European Research Council, aims to explore in more detail these previously reported interannual covariations of the magnetic and gravity fields, as well as their link with deep-Earth processes.

Cryosphere

The cryosphere session consisted of four contributions. The first presentation was about ice-mass changes of the Greenland and Antarctic Ice Sheets observed with the extended GRACE-FO time series. The datasets are well validated with multimission altimetry data and are part

[5] To learn more about CubeSats and how they are being used for NASA Earth Science and other missions, see "CubeSats and their Role in NASA's Earth Science Investigations" in the November–December 2020 issue of *The Earth Observer* [**Volume 32**, **Issue 6**, pp. 5–17—*https://go.nasa.gov/2LJ9CkO*].

[6] GIA refers to the gradual response of the solid Earth to the deglaciation of historic ice sheets.

[7] Learn more about GRACEFUL at *https://cordis.europa.eu/project/id/855677*.

[8] Learn more about the Synergy Program at *https://erc.europa.eu/funding/synergy-grants*.

of the ESA Climate Change Initiative (CCI)[9] continuation projects *GIS_cci+* and *AIS_cci+*. Independent datasets help to bridge the gap between GRACE and GRACE-FO, providing valuable information to ensure a seamless continuation of the GRACE time series with data from GRACE-FO.

The second presentation in this session discussed updated ice-mass-loss time series not only for the polar ice sheets but also mountain glaciers and ice caps. Over Greenland, low ice-mass losses during the cold years of 2017 and 2018 were followed by record melt in 2019, which was a warmer year. (Over the past decade, in response to interactions between the wobbling jet stream and topography, warm ocean air masses have been getting blocked over Greenland more frequently compared to prior centuries.) Meanwhile, in Antarctica, the ongoing rapid loss in West Antarctica dominates the mass balance, but a steady increase in snowfall was observed in the Atlantic sector of East Antarctica. These analyses provide better constraints for ice-sheet models that address sea-level projections and improve the validation of various Earth-system models and global climate models.

A detailed analysis of GRACE(-FO) data over Antarctica showed that mass changes over the whole continent can be effectively separated into several spatial patterns that could be dominated by different physical processes (i.e., glacial melting components, snow accumulation components, periodic climatic components, and GIA effects).

Finally, there was an update given on the 2011 Ice Mass Balance Intercomparison Exercise (IMBIE) with the goal of better reconciling the various reports on the Greenland Ice Sheet (GrIS) and Antarctic Ice Sheet (AIS) mass balance since 1992. IMBIE-I determined a mass balance trend for 1992-2011 for both GrIS and AIS, while IMBIE-II was open to a wider sampling of international investigative teams and provided updated results from 1992-2018. For Antarctica, the most notable contrast in results was the total value of the trend in IMBIE-II during IMBIE-I. Overall, the ice loss estimate for AIS rose by 67% (i.e., between IMBIE-1 and IMBIE-II), and the results from different techniques and teams became more consistent, owing largely to improved GIA estimates for Antarctica. Nonetheless, GIA is still most uncertain for East Antarctica and models still have considerable spread, making contemporary ice mass changes uncertain for this region.

[9] ESA's Global Monitoring of Essential Climate Variables (known for convenience as the ESA Climate Change Initiative) seeks to provide an adequate, comprehensive, and timely response to the extremely challenging set of requirements for (highly stable) long-term satellite-based products for climate that have been addressed to space agencies via the Global Climate Observing System (GCOS) and the Committee on Earth Observation Satellites (CEOS). It is exclusively concerned with addressing the explicit needs of the United Nations Framework Convention on Climate Change.

Oceanography

This section utilizes the combination of ocean state estimates from GRACE, satellite altimeters (e.g., currently Jason 3 and soon to include Jason Continuity of Service (CS), a.k.a., Sentinel-6 Michael Freilich), and *in situ* ocean floats to investigate variations in the ocean. The first presentation in this session looked into sea-level and mass-change variations in the Persian Gulf. They found high agreement between the observations from satellite altimetry and GRACE, suggesting an ocean variation mechanism that is primarily caused by boundary effects in the form of Kelvin, Rossby, and coastal waves coming in off the Indian Ocean.

The second presentation explored the difficulty that exists in measuring salinity of the global ocean, showing comparisons of *in situ* measurements (mostly from Argo floats)[10] with GRACE mass estimates after subtracting sea-ice estimates that suggest systematic biases in the salinity measurements from Argo—particularly after 2014.

The final presentation discussed the effects of various post-processing methods on global mean sea-level estimates, revealing an apparent offset between global mean sea-level estimates computed using GRACE combined with Argo data versus those from satellite altimeters (e.g., Jason 3 and Jason CS). The speaker hypothesized that instrumental drift in the microwave radiometer required for tropospheric corrections of the altimeter measurements might partly explain the offset.

This section also included a session with five "posters" presented in an online format. The posters described: work towards the future GRACE atmosphere and ocean dealiasing product, (AOD1B RL07); continuing efforts to improve computer models of ocean tides that are crucial for GRACE(-FO) data processing; the use of an ocean-bottom pressure recorder in the Arctic to test interpolating across the data gap between GRACE and GRACE-FO; estimates of global mean sea level and the effect that different processing choices has on them; and GRACE observations of ocean bottom processes and bottom water formation in the Southern Ocean.

Hydrology

This session highlighted several hydrological applications and new research avenues using GRACE and GRACE-FO data. For example, one presenter described how the uncertainties of GRACE(-FO) total water storage (TWS) products can be well approximated by a hydrology model, which is easier to access and process for most users compared to the more complex full error covariances in the GRACE(-FO) data.

[10] Argo is an international program that collects information from inside the ocean using a fleet of robotic instruments that drift with the ocean currents and move up and down between the surface and a mid-water level. To learn more, visit *https://argo.ucsd.edu*.

Other presentations showcased deep learning approaches to GRACE processing by a downscaling approach. As an example, a neural network has been trained to downscale the low-resolution signals of GRACE and GRACE-FO with the help of satellite altimetry data to create higher-resolution maps.

There were presentations on several regional case studies that provided physical applications of GRACE and GRACE-FO data. One of these described a dedicated study of the Nubian Aquifer system that showed how groundwater travels through fault systems. GRACE data, in combination with geological knowledge and *in situ* observations of the region, have opened up a new hypothesis on how groundwater flows through fault systems. Another analysis used GRACE-FO observations to quantify the water deficits during the record 2018 and 2019 drought in Europe—shown in **Figure** below. These deficits were found to increase the average summer amplitude of seasonal water storage variations by 73% (2018) and 94% (2019)—which is so severe that a recovery cannot be expected within one year assuming typical rainfall amounts. Another study described a regional study of the Tigris–Euphrates system that showed how GRACE-FO data, in combination with radar altimetry, have been used to observe dams, reservoirs, and impoundments, and could detect a recharge of the system after 15 years of dry conditions. There was also a presentation that provided new insights on how, and on what time scales, water percolates from Earth's surface to the deeper soil layers in the context of monsoon rains in Asia. Another presentation focused on how terrestrial water storage changes are affected in the case of an anthropogenic intervention in the form of a large-scale ecological restoration project in China. Another presenter described an investigation of the 2011 flooding in the Missouri River basin. To this end, GPS data were combined with GRACE data for the four years previous to and after the event to distinguish between the signals from the different hydrological compartments.

A report of a global study followed that investigated extreme events, both drought and intense rain events, in the GRACE(-FO) data record. A derived index ranks these events taking into account not only the amount of water excess or deficit, but also the affected area. A combination of GRACE TWS data with GPS observations has been assimilated into the Catchment Land Surface Model.[11] The validation of the resulting model output shows an improvement over the missing physics of the model, leading to enhanced simulations of land water processes.

Another presentation focused on a data assimilation study that uses synthetic brightness temperature data from the Advanced Microwave Scanning Radiometer for EOS (AMSR-E, on NASA's Earth Observing System (EOS) Aqua platform) along with GRACE TWS data to improve estimates of snow water equivalent over snow-covered regions. The study uses four decades of GRACE-calibrated TWS data (computed from available precipitation and surface temperature observations) and compares them to the Coupled

[11] To learn more about the Catchment Land Surface Model, see *https://go.nasa.gov/39NxnQt*.

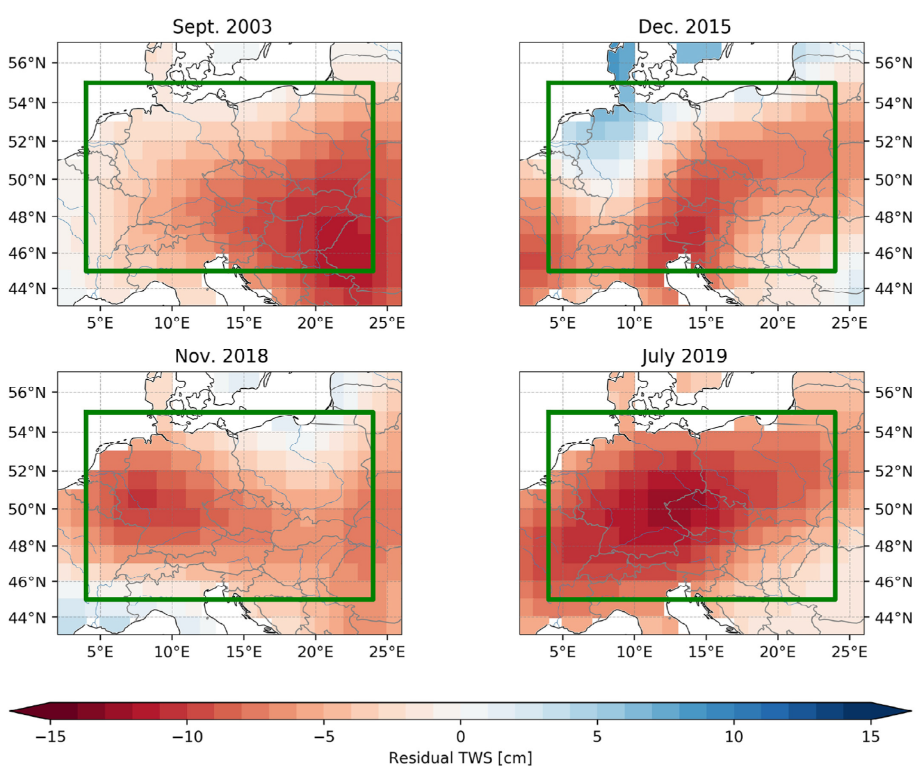

Figure. Total land water storage anomaly (relative to the long-term average for the calendar month shown) as measured with GRACE and GRACE-FO for September 2003, December 2015, November 2018, and July 2019. The inset box marks the area of Central Europe. The water deficits (including surface and groundwater) in 2018 and 2019 are the largest in the whole GRACE and GRACE-FO time span. **Image credit**: Published in *Geophysical Research Letters* [**Volume 47**, **Issue 14**, July 28, 2020—*https://doi.org/10.1029/2020GL087285*]

Model Intercomparison Project – Phase 5 (CMIP5)[12] decadal hindcast to investigate the predictive skills of the latter. At least for the first two years, the decadal hindcast provided a better prediction than classical climate projections.

Two other presentations focused on the reconstruction of GRACE data to fill the data gap between GRACE and GRACE-FO based on a combination of different machine-learning methods. Both studies concluded that the combination of several machine-learning methods is essential to cover all regions and time steps.

Multidisciplinary Science

In the multidisciplinary session, there was discussion about the synergy of GRACE(-FO) with other Earth system observations.

The first presentation in this session focused on surface mass distribution in Earth's hydrosphere and its connection to changes in Earth's rotational axis. A comparison of different rotation data (i.e., angular momentum changes) highlighted the consistency between the GRACE(-FO) solutions provided by JPL and CSR with independent angular-momentum and polar-motion datasets.

The second presentation described how observations from vector magnetometers, which are part of the GRACE-FO attitude- and orbit-control system, are valuable assets to characterize the natural variability of Earth's magnetic field and its space environment. During solar-induced magnetic storm events, GRACE-FO, in a constellation with other satellites, reveals the local time dependence of the magnetospheric ring current signature, and monitors significant plasma density enhancements at low and high latitudes. The dual-satellite constellation of GRACE-FO is most suitable to derive the persistence of auroral field-aligned currents with scale lengths of 180 km (112 mi) or longer. The data derived from nondedicated observations extend the scientific application areas of the GRACE-FO to space weather and monitoring.

The third presentation described the progress made in processing and delivering the GRACE-FO GPS Radio Occultation (GPS-RO) data products, which are used in weather and climate applications—similar to what was done with GRACE GPS-RO data. Since mid-2019, occultations from the leading GRACE-FO satellite are being recorded, and after several onboard software updates and raw data reader improvements, about 280 daily atmospheric GPS-RO sounding profiles will be available to users in early 2021 on a regular basis. The refractivity and temperature data up to an altitude of 60 km (37 mi) were compared with operational analyses from the European Centre for Medium-Range Weather Forecasts; the quality of the different measured variables continues to be evaluated.

[12] CMIP is a World Climate Research Programme initiative with the objective to better understand past, present, and future climate changes arising from natural, unforced variability, or in response to changes in radiative forcing in a multi-model context. There have thus far been six phases.

Conclusion

The first virtual GRACE-FO STM 2020 was a great success and brought together a record number of participants. The meeting once again highlighted the broad range of science analyses and applications that are supported and uniquely enabled by satellite gravimetry observations. The GRACE-FO data—available since June 2018—continue the mass-change data record at a level of performance consistent with that of GRACE. The assessment of the first GRACE-FO gravity fields by the Science Team members showed very good agreement with extrapolated GRACE estimates, as well as mass-change estimates from independent data sources. The GRACE-FO data have revealed record mass loss over Greenland in 2019, and enable vital process understanding in Earth's changing hydrosphere, including sea level, ocean currents, and land water distribution.

The successful novel laser-ranging technology—with its increased measurement accuracy—has enabled new science applications that indicate potential pathways for improved gravity and mass-change fields, in particular at submonthly time scales. Progress has been made in combining gravity data with data from other sensors to achieve improvements in resolving geophysical signals with improved spatial and temporal resolution. Atmospheric sounding profiles from the mission's GPS-RO receivers will be delivered to operational weather centers in early 2021. The multinational mission and science operations team—made up of members of the GSOC, GFZ, JPL, and CSR, together with industry support—is efficiently and successfully working to continue the long-term data record of gravity and mass change, laying the foundation for future discoveries in Earth's water cycle and mass-transport processes by the international science and science applications community. The next GSTM will be held in October 2021, hosted by JPL in Pasadena, CA—hopefully in person.

Acknowledgements

The author would like to recognize the following individuals all of whom made contributions to this article: **Felix Landerer** [JPL], **Frank Flechtner** [GFZ], **Christoph Dahle** [GFZ], **Roelof Rietbroek** [University of Twente, Netherlands], **Eva Boergens** [GFZ], **Jennifer Bonin** [University of South Florida], **Henryk Dobslaw** [GFZ], **Ingo Sasgen** [AWI], and **Carmen Boening** [JPL].

Summary of the 2020 NASA Land-Cover and Land-Use Change Annual Science Team Meeting

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Introduction

The 2020 NASA Land-Cover and Land-Use Change (LCLUC) Science Team Meeting (STM) was held virtually from October 19-21, 2020. A total of 357 participants were invited from 32 countries, out of which 258 attended the meeting from across the world. **Photo 1** is a group photo of many of the participants.

The following summary is organized approximately chronologically by day. The meeting presentations can be accessed from *https://lcluc.umd.edu/meetings/2020-nasa-lcluc-annual-science-team-meeting?page=*.

DAY ONE

Day one comprised an LCLUC program overview, two (of three) invited presentations from NASA Headquarters (HQ), and updates on the Multi-Source Land Imaging (MuSLI) program.

Chris Justice [University of Maryland, College Park (UMD)—*LCLUC Project Scientist*] was the moderator for the first day. **Photo 2** on page 23 shows speakers from NASA HQ and LCLUC Program Leads.

Welcome and LCLUC Program Overview

The meeting began with welcoming remarks from **Garik Gutman** [NASA HQ—*LCLUC Program Manager*], who shared the latest summary of program developments and achievements. This year's STM was dedicated to Anthony "Tony" Janetos, the founding Program Manager of the LCLUC program, who passed away on August 6, 2019.

Chris Justice reflected on Janetos's accomplishments and highlighted his contribution to the LCLUC program. LCLUC researchers paid tribute to Janetos by sharing their memories of the first few years of the Program—see *In Memoriam: Anthony "Tony" Janetos* on page 22.

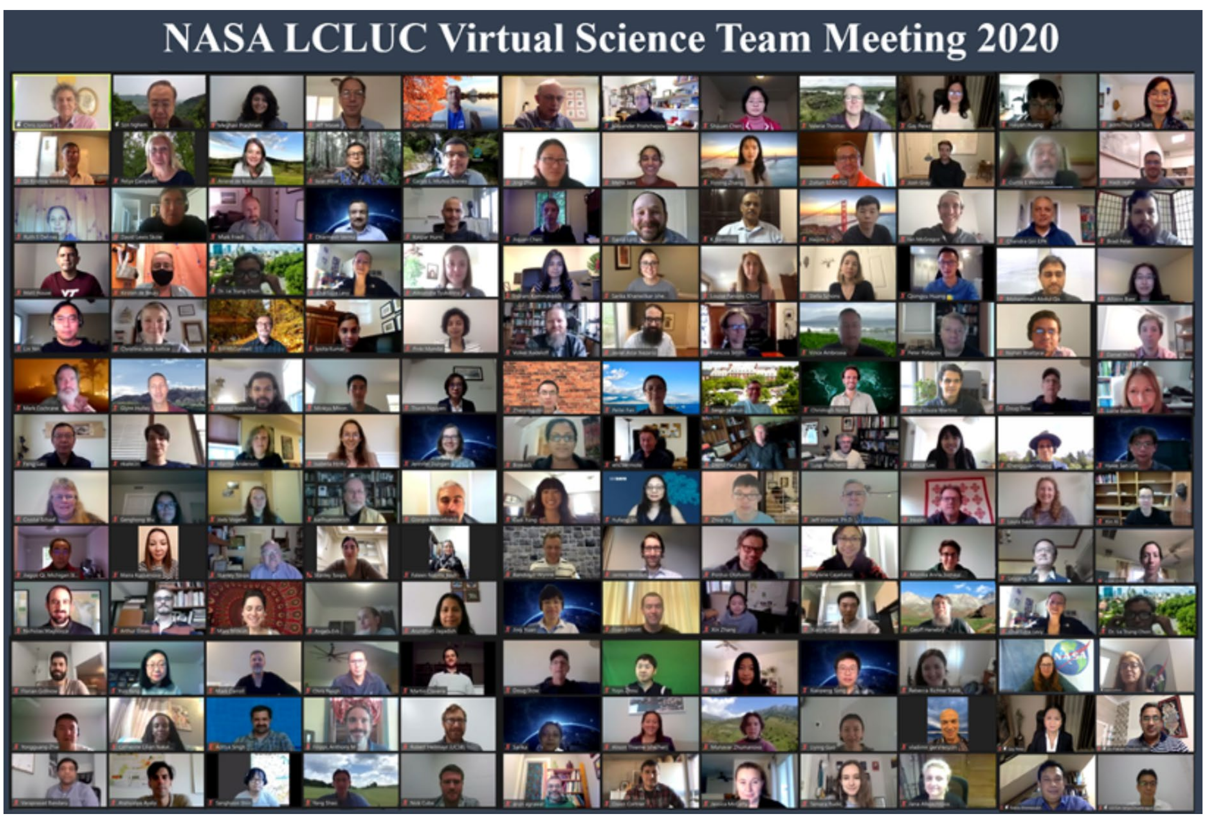

Photo 1. Group photo of many (not all) virtual participants of the 2020 LCLUC Science Team Meeting. **Photo credit**: Meghavi Prashnani

In Memoriam: Anthony "Tony" Janetos (1954-2019)

The 2020 LCLUC STM was dedicated to its founding program manager, Anthony "Tony" Janetos who passed away on August 6, 2019.

The NASA LCLUC program is saddened to report the passing of founding Program Manager, Anthony "Tony" Janetos, who was an international leader in climate change science, science policy, and global environmental assessments. He received his Ph.D. in Biology (1980) from Princeton. In 1990 he joined NASA as the Manager of the Terrestrial Ecology Program. He was NASA's representative to the U.S. Global Change Research Program (USGCRP) and the working group of the Committee on Environment and Natural Resources (CENR). In 1993, he became Chief of the Ecology and Atmospheric Chemistry Branch and Program Scientist for Landsat and the Earth Observing System (EOS) AM-1 (Terra) Platform. In 1994 he was Chief of the Earth System Models and Ecological Processes program, and in 1996 and 1997, he received Director's Award from the Science Division Mission to Planet Earth. He also advised the United Nations on climate change and co-authored a number of Intergovernmental Panel on Climate Change (IPCC) reports. Tony became LCLUC Program Manager in 1995, inviting Chris Justice to be Project Scientist to support the program. Tony had a strong vision for the LCLUC program, and he recognized that land use science is interdisciplinary and policy-relevant, plus that the socio-economic dimension is integral to understanding land use.

"Tony was a wonderful colleague and a pleasure to be with. He was direct, open, and clear-minded, and a quick learner. He had a good grounding in ecology with a strong vision for Earth science, climate change, and sustainability." —**Chris Justice**

Tony left NASA in 1999 to join the World Resource Institute as Senior Vice President and Chief of the Program. From 2003 to 2006, he served at the Heinz Center for Science, Economics, and the Environment, and in 2006 he was Director of the Joint Global Change Research Institute at the University of Maryland, College Park, where he supervised an interdisciplinary team of natural scientists, engineers, and social scientists committed to understanding the problems of global climate change and their potential solutions.

"Tony was a special person. Decades ago he pursued his vision for the Land Use Land Cover Change program and made it a reality. The entire community owes him a great deal of gratitude. We will miss his calm and steady presence." —**Ruth DeFries**

Tony was an influential leader in the global change community and contributed to the U.S. Climate Change Science Program (US CCSP), serving as co-chair of the National Assessment Synthesis Team, a body charged with providing intellectual leadership and oversight of the U.S. National Assessments of the Potential Consequences of Climate Variability and Change. He served as a Coordinating Lead Author in the Ecosystems Trends and Conditions component of the Millennium Ecosystem Assessment and contributed to the UNEP Global Biodiversity Assessment.

"Tony made significant contributions to science. He headed many advisory committees; he had a great impact on many NASA and NSF [National Science Foundation] programs and across a number of federal agencies. He was a great fun fellow to be around." —**David Skole**

Tony was instrumental in the initial development of the international GOFC-GOLD* program and served as Chair of the Steering Committee (2007-2010) and Program Chair (2010-2019). He was a member of the Scientific Steering Committee for the International Geosphere-Biosphere Programme (IGBP) Global Land Project (2009-2012). In 2013, he joined Boston University as the Director of the Frederick S. Pardee Center for the Study of the Longer-Range Future and as a Chair and Professor of the Earth and Environment Department. In 2017, he participated in NASA's Decadal Survey.

"Tony was a great colleague and mentor to many of us and we have much to thank him for. The LCLUC community will miss his scientific insight, his congeniality, and positive outlook."—**Garik Gutman**

*GOFC-GOLD stands for Global Observations for Forest Cover and Land-Use Dynamics.

Photo 2. Invited speakers from NASA HQ [*top, left to right*] **Karen St. Germain**, **Sandra Cauffman**, and **Jack Kaye** and NASA LCLUC Program Leads [*bottom, left to right*] **Garik Gutman**, **Chris Justice**, and **Krishna Vadrevu. Photo credit**: Meghavi Prashnani

Invited NASA HQ Presentations

Following these welcoming remarks, there were two presentations from representatives of NASA HQ to place the LCLUC Program within the larger context of NASA's Earth Science Division (ESD). **Karen St. Germain** [NASA HQ—*Director of the ESD*], who became Director in June 2020, shared her perspective and near-term priorities of the ESD for the coming decade. She acknowledged that the ESD has holistic end-to-end programs focusing on research, development, and observations useful for decision-making. She emphasized the importance of making actionable information available to decision makers at all levels: federal, local, tribal, emergency responders, and non-government organizations.

Following on St. Germain's comments, **Jack Kaye** [NASA HQ—*Associate Director for Research of the ESD*] emphasized that interdisciplinary science and international engagement are critical components of the ESD. He noted that for a long time, the LCLUC Program has contributed substantially to achieving this goal by integrating natural and social sciences in its projects and collaborating with regional scientists worldwide.

Multi-Source Land Imaging Program Overview

The MuSLI program provides support to researchers to utilize multiple sources of Earth observations for a better characterization of land-use and coastal processes. **Jeff Masek** [NASA's Goddard Space Flight Center (GSFC)—*MuSLI Project Scientist*] explained the evolution of the MuSLI program over the past six years since its inception and how it serves as a bridge between the supply and demand side of the satellite data. On the supply side, a number of satellite datasets are available since 1972, but in the last decade the availability of remote sensing data exploded, especially due to the European Space Agency's Sentinels[1] and other national and international missions, e.g., VENμS (Israel and France),[2] Resourcesat (India),[3] and RADARSAT (Canada).[4] Also, commercial very high-resolution satellite data from private companies (e.g., Maxar Technologies[5] and Planet[6]) have become more readily available. On the demand side, the land science and application user communities have a need for dense time series of imagery to quantify the rapid LCLUC including vegetation phenology, surface hydrology, and land management practices. Integration of the multi-source satellite data is a complex process that entails integration of multiple datasets with different formats while simultaneously maintaining the spatial and temporal consistency including calibration, and developing products to meet user needs. Masek concluded his presentation illustrating one of the MuSLI products; he showed the continental-scale land surface phenology from the Harmonized Landsat Sentinel (HLS) database (combining data from Landsat 8 and Sentinel-2)—see **Figure 1** on page 24.

Following Masek's address, eight MuSLI scientists presented their project updates, starting with updates from three MuSLI Type-1 projects aimed at building continental-scale products. Algorithms for these projects were prototyped in the first stage of the MuSLI round and are currently being implemented on a continental scale in their second stage. Following this were presentations on five Type-2 MuSLI projects, which are presently building regional-scale prototypes

[1] The European Space Agency has developed the Sentinels to meet the operational needs of its Copernicus programme. To learn more, visit *https://www.esa.int/Applications/Observing_the_Earth/Copernicus/Overview3*.

[2] VENμS is the first cooperative Earth observation program of Israel (ISA) and France (CNES). The minisatellite mission is being developed jointly by the Israeli Space Agency (ISA) and the French Centre National d'Études Spatiale (CNES), under a memorandum of understanding between the two space agencies.

[3] The Resourcesat satellites are built by the Indian Space Research Organisation (ISRO), which continues the remote sensing data services provided by the Indian Remote Sensing Series (IRS)-1C and -1D.

[4] RADARSAT is a Canadian remote sensing Earth observation satellite program overseen by the Canadian Space Agency (CSA).

[5] Maxar Technologies is a space technology company headquartered in Westminster, CO, specializing in manufacturing communication, Earth observation, radar, and on-orbit servicing satellites, satellite products, and related services.

[6] Planet is an Earth-observing remote sensing company in San Francisco, CA. It currently operates two smallsat constellations (DOVE and RapidEye).

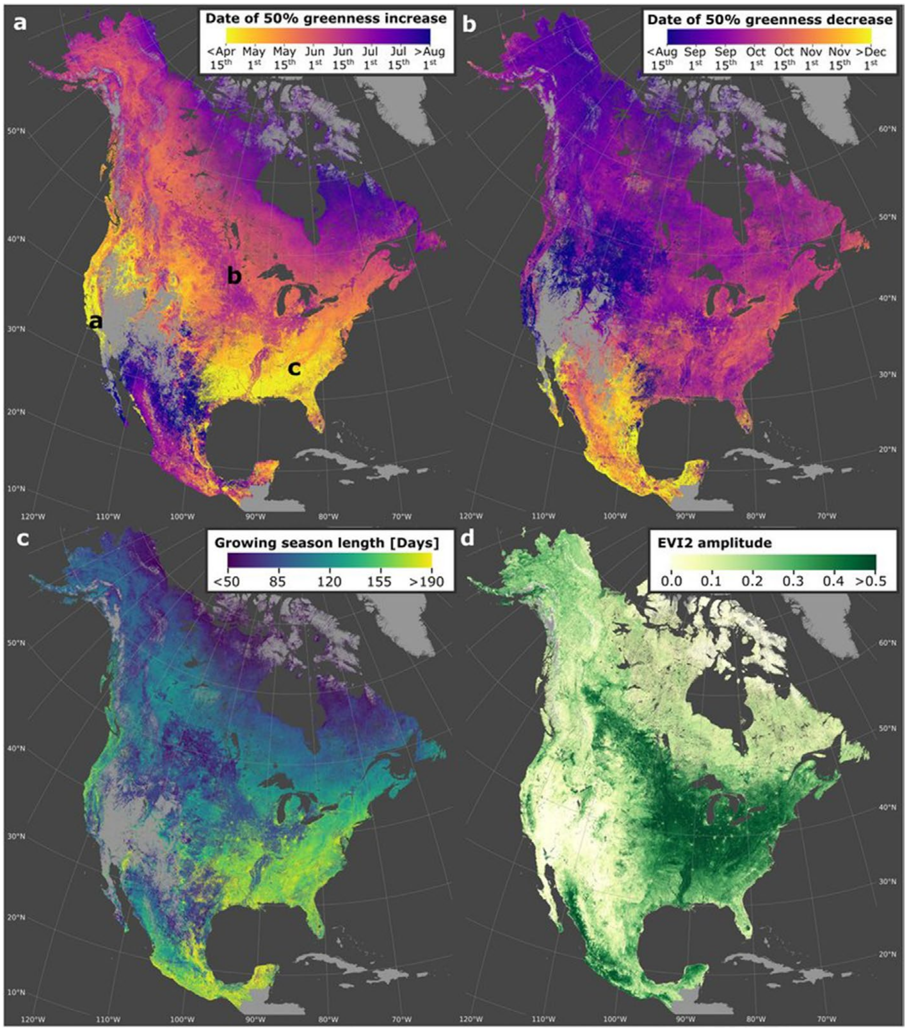

Figure 1. Continental patterns in the timing of spring green-up [*top left*] and fall green-down [*top right*] show strong geographic variation related to climate forcing and land use. Continental-scale patterns in growing season length [*bottom left*] and two-band Enhanced Vegetation Index (EVI2) amplitude [*bottom right*] reflect similar geographic patterns. **Image credit**: Mark Friedl [Boston University]

where algorithms are still being developed. All eight talks covered a variety of MuSLI applications, including imaging of seasonal dynamics of land surface, circumpolar albedo, burned area estimation, urban heat islands, and crop yield assessments. **Garik Gutman** summed up the day discussing the accomplishments and future direction for the MuSLI program.

DAY TWO

The second day focused on the South/Southeast Asia Research Initiative (SARI) with several presentations that provided updates on various aspects of the initiative and a panel discussion on the SARI synthesis. **Krishna Vadrevu** [NASA's Marshall Space Flight Center (MSFC)—*LCLUC Deputy Program Manager, SARI Project Scientist*] chaired the second day's activities.

Update on SARI Activities

Krishna Vadrevu kicked off the second day, providing an update on SARI for the LCLUC ST. He presented various activities and studies carried out under SARI since its inception, including regional meetings, capacity building training, publications, collaborations, solicitations, and field visits. Over the past five years, 22 different projects were funded by the LCLUC program under the SARI umbrella. Of these, 12 are in South Asia and 10 in Southeast Asia. These 22 projects involved more than 250 U.S. and international scientists from over 150 organizations. To date, nearly 250 papers have been published in peer-reviewed journals and 12 different special issues have been produced through SARI collaborations. The SARI program organized several regional meetings in countries such as Vietnam, Thailand, Indonesia, Burma, and India, [7] involving space agencies, governmental and non-governmental organizations, local universities, students, and professionals from related sectors. These regional meetings have helped U.S. scientists develop international collaborations in different countries, useful for validation of several NASA satellite datasets, testing novel algorithms, and sharing science results and information with local decision-makers. The SARI program is involved in organizing multiple capacity building and training events in developing countries to train young researchers on novel

[7] For a recent example, see "Summary of the 2019 SARI Sustainable Forestry in South Asia Meeting" in the September–October 2020 issue of *The Earth Observer* [**Volume 32**, **Issue 5**, pp. 21–26—*https://go.nasa.gov/3jzoj6f*].

remote sensing and geospatial technology and tools useful for research and applications.

Presentations on LCLUC Issues in South and Southeast Asia

After the programmatic overview of SARI, the focus turned to summaries of the individual SARI projects. As with the programmatic presentations, the reports on individual SARI projects highlighted specific LCLUC issues in South and Southeast Asia. Over the last several decades, this area of the world has experienced extremely rapid land-use and land-cover changes. Two SARI Principal Investigators (PIs) gave overview presentations on SARI activities in Southeast and South Asia respectively, which are summarized in what follows.

Overview Presentations

Jefferson Fox [East-West Center, Hawaii] presented an overview of identifying trends and ongoing issues in Southeast Asia—see **Figure 2**. There has been a rapid expansion of large-scale agro-businesses in the region, especially rubber and oil palm, expanding to other tree crops, orchards, coffee, and fast-growing trees (for pulp and paper)—all of which SARI PIs have investigated. For future projects, Fox suggested the LCLUC program address other drivers of LCLUC besides rice, palm, and rubber. He also suggested having more projects covering the entire Southeast Asia region to capture a wider range of LCLUC issues.

Ruth DeFries [Columbia University] presented an overview of LCLUC projects in the South Asia region—see **Figure 3**—stressing that the region possesses very distinctive characteristics compared to the rest of the world, making the LCLUC studies important for the sustainable development of the region. This region is experiencing water stress, crop stress, a strain on the energy system, rapid LCLUC, massive agricultural expansion and intensification, with high-density and increasing population. However, on a positive note, South Asia has a lot of degraded lands that could potentially be put to good use for the benefit of people's livelihoods, environmental restoration, and climate mitigation. DeFries explained that South Asia presents a challenge for land-cover/use assessment because there are large areas with sparse vegetation, scattered forests, trees outside forests, fragmented

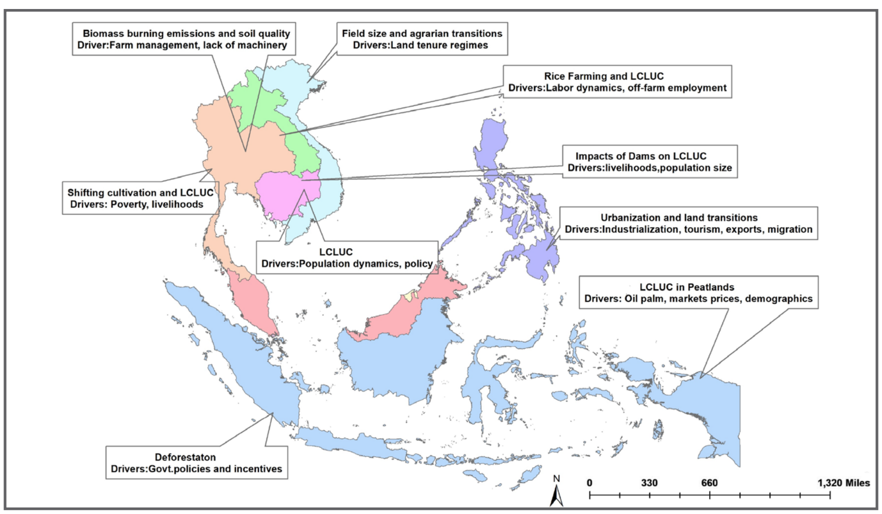

Figure 2. LCLUC drivers in Southeast Asia as identified by LCLUC SARI project PIs and covered in Jefferson Fox's overview presentation. **Image credit**: Krishna Vadrevu

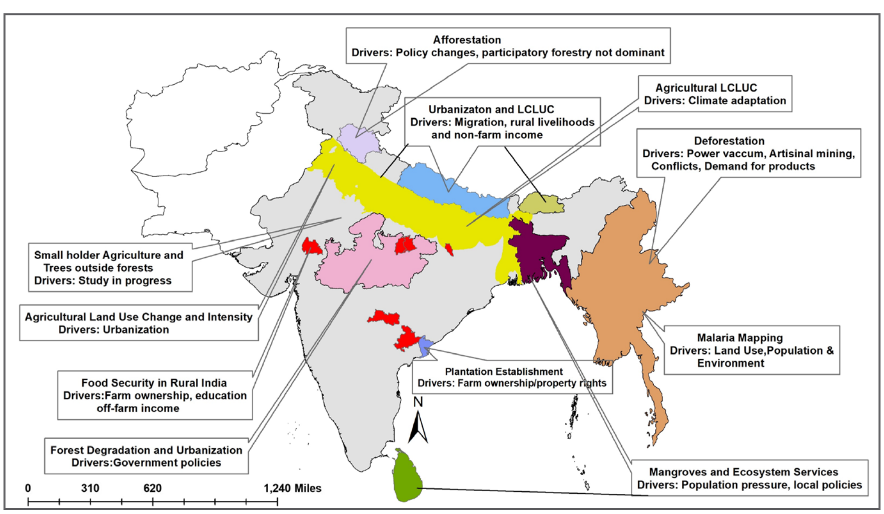

Figure 3. LCLUC drivers in South Asia as identified by LCLUC SARI project PIs and covered in Ruth Defries' overview presentation. **Image credit**: Krishna Vadrevu

Photo 3. Space Agency Leads from South/Southeast Asia. [*Top row, left to right*] **Prakash Chauhan** [ISRO], **Shinichi Sobue** [JAXA], **Lam Dao Nguyen** [VNSC] and [*bottom row*] **Tatia Chuentragun** [GISTDA], **Rokhis Khomruddin** [LAPAN], and **Gay Perez** [Philippines Space Agency]. **Photo credit**: Meghavi Prashnani

urban areas, and smallholder agriculture systems. She emphasized that the new, very-high-resolution data and new sensors [e.g., NASA's Global Ecosystem Dynamics Investigation (GEDI)[8] mission]—along with strong scientific partnerships and collaborations developed during SARI—have the potential to address these issues.

Updates from Regional Space Agencies

Representatives from six regional space agencies in South and Southeast Asia also gave updates on their agency's activities. The organizations included the Indian Space Research Organization (ISRO), Vietnam National Space Center (VNSC), Thai Geo-Informatics and Space Technology Development Agency (GISTDA), Japan Aerospace Exploration Agency (JAXA), Philippines Space Agency (PhilSA), and the Indonesian National Institute of Aeronautics and Space [Lembaga Penerbangan dan Antariksa Nasional (LAPAN)]. (These speakers are shown and named in **Photo 3**.)

Panel Discussion Toward SARI Synthesis

Chris Justice and **Krishna Vadrevu** moderated a panel discussion called "Toward SARI Synthesis." To date, there have been 22 SARI projects completed. The purpose of this discussion was to plan for the next stage of analysis called *SARI synthesis*. The panel consisted of experts of LCLUC science in the SARI region. **Karen Seto** [Yale University], **David Skole** [Michigan State University], and **Atul Jain** [University of Illinois Urbana Champaign] represented activities in South Asia. **Peter Potapov** [UMD], **Son Nghiem** [JPL], and **Arianne De Bremond** [UMD] represented activities in Southeast Asia.

Each panelist was asked to share his or her unique perspective on moving toward SARI Synthesis and to answer the following questions: *What is your perspective on moving toward SARI Synthesis? What do* you *see as the biggest challenge in terms of advancing land use change science in the region? What would you like to see happen?*

There was a common theme in the responses from panelists that land use studies in this region should be conceptualized from a South and Southeast Asian perspective as opposed to following western prototypes. Additionally, the panelists were unanimous in their assessment that synthesis needs to occur through interdisciplinary studies of diverse domains of Earth science—e.g., ecology, hydrology, geophysics, geochemistry, and atmospheric science. Furthermore, in order to obtain a better environment, equity, land tenure, food security, and wellbeing of society, the physical aspects of land-use change mentioned above must be studied in conjunction with human dimensions of the issue. So, the consensus arising from the discussion was that there is a need for an integrated science-driven approach with a regional outlook involving and encouraging regional scientists. The panelists stressed the importance of strengthening urban studies in the SARI region. Additionally, they noted that there has been a rapid and massive expansion of infrastructure, dams, roads, solar energy installations, canals, and railways in the SARI region; hence, SARI projects can help study the cause and impacts of these land-use changes.

DAY THREE

The third day featured the third invited presentation from NASA HQ, followed by project introductions from the recent 2019 LCLUC selections involving Early Career Scientists (ECS), followed by a discussion on the international Global Observations of Forest Cover and Land-use Dynamics (GOFC–GOLD) program[9] and the LCLUC future directions. **Garik Gutman** moderated all sessions.

Invited NASA HQ Presentation

Sandra Cauffman [NASA HQ—*Deputy Director of the ESD*] discussed the significance of the LCLUC program within the ESD and how products and information from LCLUC projects have been providing useful solutions to the demands of national and

[8] GEDI is a space-based lidar that is mounted on the International Space Station. For more information, visit *https://gedi.umd.edu*.

[9] GOFC–GOLD is an integrated project within the program Global Terrestrial Observing System (GTOS), which is supported by Integrated Global Observing Strategy (IGOS). The project's main objective is to provide a forum for sharing international information, observation and coordination of data, and establishing a structure for monitoring long-term systems.

international agencies, such as the U.S. Agency for International Development (USAID), U.S. Department of Agriculture (USDA), and U.S. Forest Service. The LCLUC program is successfully addressing problems that are of societal relevance and impetus for understanding the sustainability, vulnerability, and resilience of human land-use and terrestrial ecosystems. The program is unique and its strength lies in integrating physical and social sciences to understand land-use change processes at various spatial scales.

Presentations from Early Career Scientists

Garik Gutman began the session with a brief introduction of the nine new LCLUC projects[10] and their investigators from the ROSES 2019 selections,[11] which was a call for Early Career Scientists. Gutman gave a brief overview of the program, explaining to the new PIs about the LCLUC website's features and how their projects should strengthen the GOFC–GOLD regional networks involving local researchers. Gutman emphasized that the project metadata are vital for the Program, and that PIs are required to submit their project's metadata. There is an existing LCLUC metadata page on the program website, and a metadata sub-portal will soon be developed to improve metadata searching.

After Gutman spoke, each of the early career LCLUC PIs gave presentations, elaborating on the objectives and expected outcomes of their specific projects as well as their societal relevance. These new projects aim to investigate a variety of themes in land use science such as agriculture, forests, climate change, food security, market forces, and biodiversity, as well as their socioeconomic drivers and impacts. These recent nine LCLUC 2019 selections will contribute to the regional GOFC-GOLD networks.[12] Several of them fall under the Red Latinoamericana de Teledeteccion e Incendios Forestales (RedLaTIF) regional network, which covers Latin America. New PIs are requested to strengthen the GOFC–GOLD network in their project region through collaborating with local scientists.

Discussion on Future Directions for LCLUC Program

Chris Justice gave a presentation on the Program's future direction to set the tone for a discussion among participants. The use of very-high-resolution data and integration of data from different satellite systems, such as the Harmonized Landsat Sentinel (HLS) project, will continue to be developed. The program would like to see products prototyped by MuSLI and transition to operational production. Connections between LCLUC and the NASA Applied Sciences Program will likely be strengthened, and it's likely that the impacts of climate change on land-use will receive more attention. The discussion participants concurred that there is a need for a plan to develop another regional initiative post SARI, based on solid scientific rationale. A couple of regional meetings might help scope such an initiative and inform future solicitations. Suggestions included Latin America and sub-Saharan Africa. There was a discussion on designing a SARI synthesis by a panel of eminent scientists and innovators in LCLUC science in the South and Southeast Asian region. They suggested that the SARI synthesis be framed in the context of existing SARI research undertaken by U.S. and the national and international scientists working in the region.

Conclusion

The meeting concluded with final remarks from **Garik Gutman**. The next Research Opportunities in Space and Earth Sciences (ROSES) call will also target early-career scientists and will follow a two-step solicitation process. The focus will be on the detection and assessment of hotspots via the MuSLI approach. A hotspot in this context is defined as a rapidly changing land-use/cover activity in a particular region over the last several years, characterized by societal significance and impacts, and national to regional importance. The goal is to expand the global hotspot inventory of the LCLUC program. More information about this solicitation can be found in ROSES 2021, to be published in mid-February 2021. The three-day 2020 Science Team Meeting was the Program's first virtual meeting. Participants requested to have a virtual option in future meetings. Next year, the LCLUC Program will be celebrating its 25th Anniversary with current researchers and alumni from the quarter century LCLUC journey. The 2020 Science Team Meeting successfully brought together LCLUC researchers from the U.S. and elsewhere around the world to report on research progress, strengthen partnerships and collaborations, highlight ongoing LCLUC issues, and address community concerns. During the meeting, NASA HQ representatives echoed, that for the rapid advancement of space science, it is crucial to bring science together from corners of the world through collaboration, open science, easy data sharing, and incentive programs—despite political distractions and conflicts. They also emphasized that NASA is highly committed to inclusive, equitable, accessible, and diverse work environments. Inclusion has taken its place alongside safety, integrity, teamwork, and excellence, as the fifth core value of the agency. ■

[10] These 2020 projects are listed along with all other current and past LCLUC projects at *https://lcluc.umd.edu/content/projects*. Click on the *South Asia* and *Southeast Asia* tabs to see the specific projects in these regions.

[11] For more information on this call, see *https://nspires.nasaprs.com/external/solicitations/summary!init.do?solId=%7B716BCFE6-52B4-DB7F-B79A-59F3E7EE14A2%7D&path=open*.

[12] For more information on the GOFC–GOLD networks, including a map showing them all geographically, see *https://gofcgold.umd.edu/regional-networks*.

Land Ecosystems are Becoming Less Efficient at Absorbing CO_2

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EDITOR'S NOTE: This article is taken from *nasa.gov*. While this material contains essentially the same content as the original release, it has been rearranged and wordsmithed for the context of *The Earth Observer*.

Land ecosystems currently play a key role in mitigating climate change. The more carbon dioxide (CO_2) plants and trees absorb during *photosynthesis*, the process they use to make food, the less CO_2 remains trapped in the atmosphere where it can cause temperatures to rise. But scientists have identified an unsettling trend—as levels of CO_2 in the atmosphere increase, 86% of land ecosystems globally are becoming progressively less efficient at absorbing it. To watch a video on this topic, see the **Figure** below.

Because CO_2 is a main 'ingredient' that plants need to grow, elevated concentrations of it cause an increase in photosynthesis, and consequently, plant growth—a phenomenon aptly referred to as the *CO_2 fertilization effect* (CFE). CFE is considered a key factor in the response of vegetation to rising atmospheric CO_2 as well as an important mechanism for removing this potent greenhouse gas from our atmosphere—but that may be changing.

In a study published in the journal *Science*[1] on December 1, 2021, researchers analyzed multiple field, satellite-derived, and model-based datasets to better understand what effect increasing levels of CO_2 may be having on CFE. Their findings have important implications for the role plants can be expected to play in offsetting climate change in the years to come.

"In this study, by analyzing the best available long-term data from remote sensing and state-of-the-art land-surface models, we have found that since 1982, the global average CFE has decreased steadily from 21% to 12% per 100 ppm of CO_2 in the atmosphere," said study co-author **Ben Poulter** [NASA's Goddard Space Flight Center (GSFC)]. "In other words, terrestrial ecosystems are becoming less reliable as a temporary climate change mitigator."

[1] The study can be viewed at *https://science.sciencemag.org/content/370/6522/1295.full*.

What's Causing It?

Without this feedback between photosynthesis and elevated atmospheric CO_2, Poulter said we would have seen climate change occurring at a much more rapid rate. But scientists have been concerned about how long the CFE could be sustained before other limitations on plant growth kick in.

For instance, while an abundance of CO_2 won't limit growth, a lack of the other necessary components of photosynthesis—e.g., water, nutrients, or sunlight—will. To determine why the CFE has been decreasing, the study team took the availability of these other elements into account.

"According to our data, what appears to be happening is that there's both a moisture limitation as well as a nutrient limitation coming into play," Poulter said. "In the tropics, there's often just not enough nitrogen or phosphorus, to sustain photosynthesis, and in the high-latitude temperate and boreal regions, soil moisture is now more limiting than air temperature because of recent warming."

In effect, climate change is weakening plants' ability to mitigate further climate change over large areas of the planet.

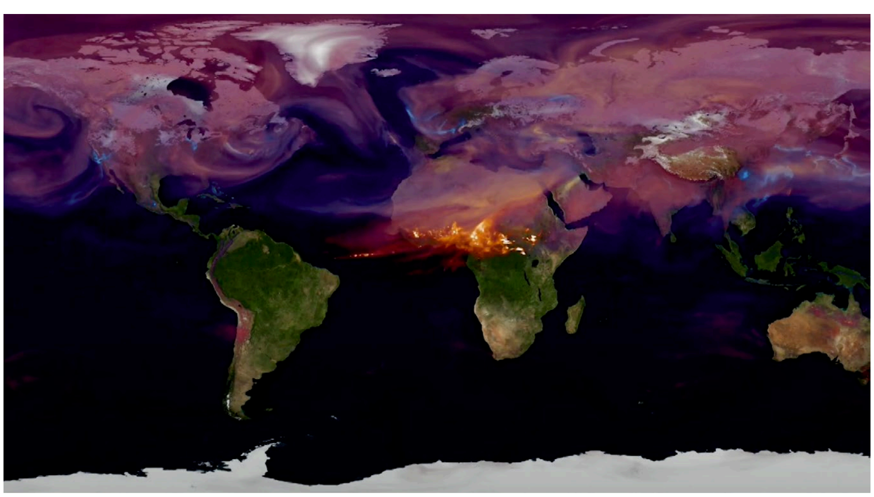

Figure. A video on this topic, titled *Plants Are Struggling to Keep Up with Rising Carbon Dioxide Concentrations*, is available on the NASA Goddard YouTube channel at *https://go.nasa.gov/3t6dYTR*. **Credit**: NASA's Goddard Space Flight Center/Scientific Visualization Studio/Katy Mersmann

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Water Limitations in the Tropics Offset Carbon Uptake from Arctic Greening

Lara Streiff, NASA's Goddard Space Flight Center, lara.g.streiff@nasa.gov

EDITOR'S NOTE: This article is taken from *nasa.gov*. While this material contains essentially the same content as the original release, it has been rearranged and wordsmithed for the context of *The Earth Observer*.

More plants and longer growing seasons in the northern latitudes have converted parts of Alaska, Canada, and Siberia to deeper shades of green. Some studies translate this Arctic greening to a greater global carbon uptake. But new research shows that as Earth's climate is changing, increased carbon absorption by plants in the Arctic is being offset by a corresponding decline in the tropics.

"This is a new look at where we can expect carbon uptake to go in the future," said **Rolf Reichle** [NASA's Goddard Space Flight Center (GSFC), Global Modeling and Assimilation Office (GMAO)].

Reichle is one of the authors of a study, published December 17, 2020, in *AGU Advances*,[1] which combines satellite observations over 35 years from the National Oceanic and Atmospheric Administration's (NOAA's) Advanced Very High Resolution Radiometer (AVHRR) with computer models, including water limitation data from NASA's Modern-Era Retrospective analysis for Research and Applications model, Version 2 (MERRA-2).

Together, these provide a more accurate estimate of *global primary productivity* (GPP)—a measure of how well plants convert carbon dioxide and sunlight to energy and oxygen via photosynthesis, for the time span between 1982 to 2016—see **Figure**.

Arctic Gains and Tropical Losses

Plant productivity in the frigid Arctic landscape is limited by the lengthy periods of cold. As temperatures warm, the plants in these regions are able to grow more densely and extend their growing season, leading to an overall increase in photosynthetic activity, and subsequently greater carbon absorption in the region over the 35-year time span.

However, buildup of atmospheric carbon concentrations has had several other rippling effects. Notably, as carbon has increased, global temperatures have risen, and the atmosphere in the tropics (where plant productivity is limited by the availability of water) has become drier. Recent increases in drought and tree mortality in the Amazon rainforest are examples of this. Productivity and carbon absorption over land near the equator have gone down over the same time period as Arctic greening has occurred, canceling out any net effect on global productivity.

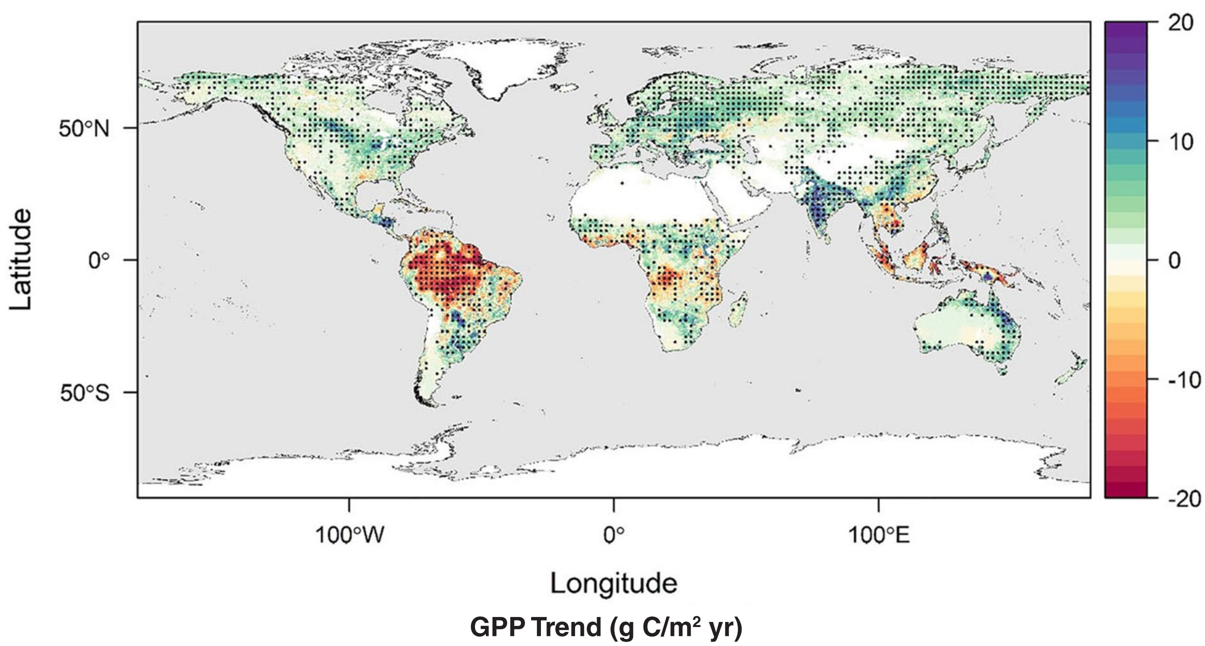

Figure. A map of the world shows the changes in global gross primary productivity (GPP), an indicator of carbon uptake, from 1982–2016. Each dot indicates a region with a statistically significant trend. **Credit**: Nima Madani [NASA/Jet Propulsion Laboratory]

[1] The study can be viewed at *https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2020AV000180*. The data produced from this study are publicly accessible at *https://doi.org/10.3334/ORNLDAAC/1789*.

Adding Satellites to Productivity Models

Previous model estimates suggested that the increasing productivity of plants in the Arctic could partially compensate for human activities which release atmospheric carbon, e.g., the burning of fossil fuels. But these estimates relied on models that calculate plant productivity based on the assumption that they *photosynthesize* (convert carbon and light) at a given efficiency rate.

In reality, many factors can have an effect on plants' productivity. Including satellite records like those from AVHRR provide scientists with consistent measurements of the global photosynthetic plant cover that can help account for variable events such as pest outbreaks and deforestation—which previous models do not capture. These can impact the global vegetation cover and productivity.

"There have been other studies that focused on plant productivity at global scales," said lead author of the study **Nima Madani** [NASA/Jet Propulsion Laboratory], which also includes scientists from the University of Montana. "But we used an improved remote sensing model to have a better insight into changes in ecosystem productivity." This model uses an enhanced light use efficiency algorithm, which combines multiple satellites' observations of photosynthetic plant cover and variables such as surface meteorology.

"The satellite observations are critical especially in regions where our field observations are limited, and that's the beauty of the satellites," Madani said. "That's why we are trying to use satellite remote sensing data as much as possible in our work."

It was only recently that the satellite records began to show these emerging trends in shifting productivity. According to Reichle, "The modeling and the observations together, what we call *data assimilation*, is what really is needed." The satellite observations train the models, while the models can help depict Earth system connections such as the opposing productivity trends observed in the Arctic and tropics.

Brown Is the New Green

The satellite data also revealed that water limitations and decline in productivity are not confined to the tropics. Recent observations show that the Arctic's greening trend is weakening, with some regions already experiencing browning.

"I don't expect that we have to wait another 35 years to see water limitations becoming a factor in the Arctic as well," said Reichle. We can expect that the increasing air temperatures will reduce the carbon uptake capacity in the Arctic and boreal biomes in the future. Madani said Arctic boreal zones in the high latitudes that once contained ecosystems constrained by temperature are now evolving into zones limited by water availability like the tropics.

These ongoing shifts in productivity patterns across the globe could affect numerous plants and animals, altering entire ecosystems. That in turn can impact food sources and habitats for various species, including endangered wildlife, and human populations. ■

Land Ecosystems are Becoming Less Efficient at Absorbing CO_2

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Next Steps

The international science team found that when remote-sensing observations were taken into account—including vegetation index data from the Advanced Very High Resolution Radiometer (AVHRR)[2] and the Moderate Resolution Imaging Spectroradiometer (MODIS)[3] instruments—the decline in CFE is more substantial than current land-surface models have shown. Poulter said this is because modelers have struggled to account for nutrient feedbacks and soil moisture limitations—due, in part, to a lack of global observations of them.

"By combining decades of remote sensing data like we have done here, we're able to see these limitations on plant growth. As such, the study shows a clear way forward for model development, especially with new remote sensing observations of vegetation traits expected in coming years," he said. "These observations will help advance models to incorporate ecosystem processes, climate, and CO_2 feedbacks more realistically."

The results of the study also highlight the importance of the role of ecosystems in the global carbon cycle. According to Poulter, going forward, the decreasing carbon-uptake efficiency of land ecosystems means we may see the amount of CO_2 remaining in the atmosphere after fossil fuel burning and deforestation start to increase, shrinking the remaining carbon budget.

"What this means is that to avoid warming of between 1.5 and 2 °C (or 2.7 and 3.6 °F) and the associated climate impacts, we need to adjust the remaining carbon budget to account for the weakening of the plant CFE," he said. "And because of this weakening, land ecosystems will not be as reliable for climate mitigation in the coming decades." ■

[2] AVHRR instruments have flown on National Oceanic and Atmospheric Administration (NOAA) Polar Operational Environmental Satellites (POES) and European MetOp platforms. The last AVHRR instrument launched on November 18, 2018, on MetOp C.

[3] MODIS flies on NASA's Terra and Aqua platforms.

2020 Tied for Warmest Year on Record, NASA Analysis Shows

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EDITOR'S NOTE: This article is taken from *nasa.gov*. While this material contains essentially the same content as the original release, it has been rearranged and wordsmithed for the context of *The Earth Observer*.

Earth's global average surface temperature in 2020 tied with 2016 as the warmest year on record.

Continuing the planet's long-term warming trend, the year's globally averaged temperature was 1.84 °F (1.02 °C) warmer than the baseline 1951–1980 mean, according to scientists at NASA's Goddard Institute for Space Studies (GISS). The year 2020 edged out 2016 by a very small amount, within the margin of error of the analysis, making the years effectively tied for the warmest year on record.

"The last seven years have been the warmest seven years on record, typifying the ongoing and dramatic warming trend," said **Gavin Schmidt** [GISS—*Director*]. "Whether one year is a record or not is not really that important—the important things are long-term trends. With these trends, and as the human impact on the climate increases, we have to expect that records will continue to be broken."

A Warming, Changing World

Tracking global temperature trends provides a critical indicator of the impact of human activities—specifically, greenhouse gas emissions—on our planet. Earth's average temperature has risen more than 2 °F (1.2 °C) since the late nineteenth century.

Rising temperatures are causing phenomena such as loss of sea ice and ice sheet mass, sea level rise, longer and more intense heat waves, and shifts in plant and animal habitats. Understanding such long-term climate trends is essential for the safety and quality of human life, allowing humans to adapt to the changing environment in ways such as planting different crops, managing our water resources, and preparing for extreme weather events.

Ranking the Records

A separate, independent analysis by the National Oceanic and Atmospheric Administration (NOAA) concluded that 2020 was the second warmest year in their record—behind 2016. NOAA scientists use much of the same raw temperature data in their analysis but have a different baseline period (1901–2000) and methodology. Unlike NASA, NOAA also does not infer temperatures in polar regions lacking observations. This accounts for much of the difference between NASA and NOAA records.

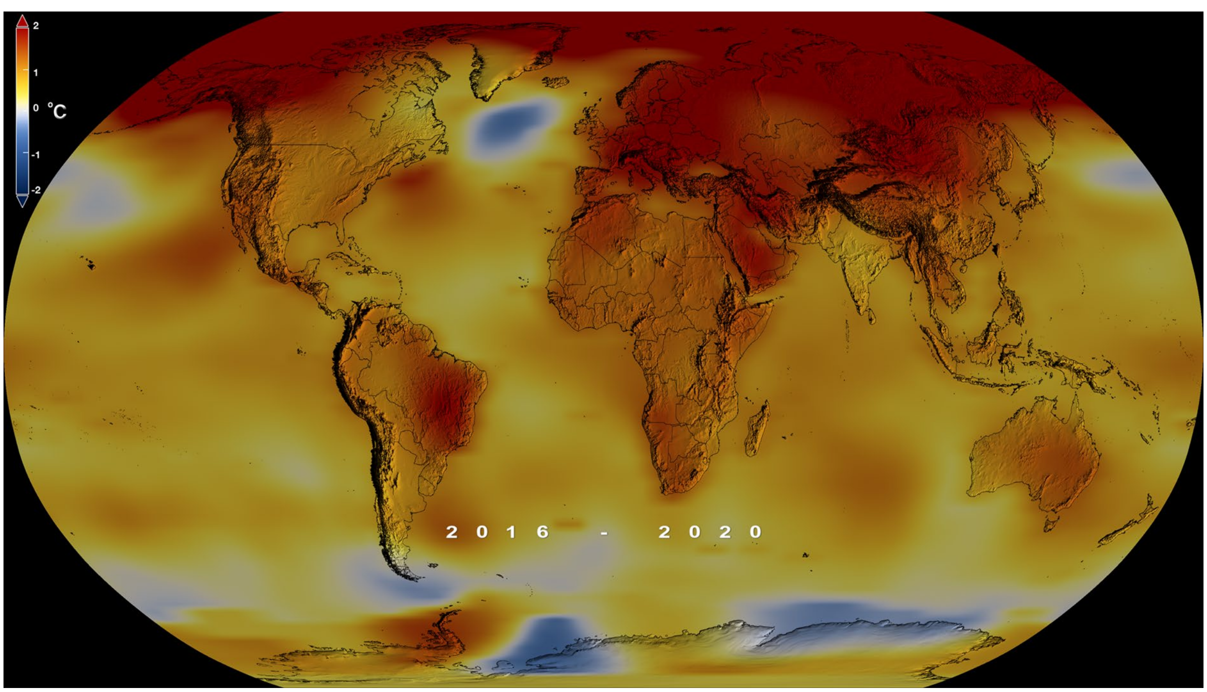


Figure. This map represents the five-year global temperature anomalies from 2016-2020. Normal temperatures are the average over the 30-year baseline period 1951-1980. To view the visualization visit *https://svs.gsfc.nasa.gov/4882* **Image credit:** NASA's Scientific Visualization Studio

Like all scientific data, these temperature findings contain a small amount of uncertainty—in this case, mainly due to changes in weather station locations and temperature measurement methods over time. The GISS temperature analysis (GISTEMP) is accurate to within 0.1 °F (~0.06 °C) with a 95% confidence level for the most recent period.

Beyond a Global, Annual Average

While the long-term trend of warming continues, a variety of events and factors contribute to any particular year's average temperature. Two separate events changed the amount of sunlight reaching the Earth's surface. The Australian bush fires during the first half of the year burned 46 million acres (~190,000 km^2) of land, releasing smoke and other particles more than 18 mi (~29 km) high in the atmosphere, blocking sunlight and likely cooling the atmosphere slightly. In contrast, global shutdowns related to the ongoing coronavirus (COVID-19) pandemic reduced particulate air pollution in many areas, allowing more sunlight to reach the surface and producing a small but potentially significant warming effect. These shutdowns also appear to have reduced the amount of carbon dioxide (CO_2) emissions last year, but overall CO_2 concentrations continued to increase, and since warming is related to cumulative emissions, the overall amount of avoided warming will be minimal.

The largest source of year-to-year variability in global temperatures typically comes from the El Niño-Southern Oscillation (ENSO), a naturally occurring cycle of heat exchange between the ocean and atmosphere. While the year has ended in a negative (cool—La Niña) phase of ENSO, it started in a slightly positive (warm—El Niño) phase, which marginally increased the average overall temperature. The cooling influence from the negative phase is expected to have a larger influence on 2021 than 2020.

"The previous record warm year—2016—received a significant boost from a strong El Niño. The lack of a similar assist from El Niño this year is evidence that the background climate continues to warm due to greenhouse gases," Schmidt said.

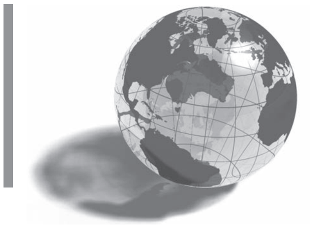
The 2020 GISS values represent surface temperatures averaged over both the whole globe and the entire year. Local weather plays a role in regional temperature variations, so not every region on Earth experiences similar amounts of warming even in a record year. According to NOAA, parts of the continental U.S. experienced record high temperatures in 2020, while others did not.

In the long term, parts of the globe are also warming faster than others. Earth's warming trends are most pronounced in the Arctic, which the GISTEMP analysis shows is warming more than three times as fast as the rest of the globe over the past 30 years, according to Schmidt. The loss of Arctic sea ice—whose annual minimum area is declining by about 13% per decade—makes the region less reflective, meaning more sunlight is absorbed by the oceans and temperatures rise further still. This phenomenon, known as *Arctic amplification*, is driving further sea ice loss, ice sheet melt and sea level rise, more intense Arctic fire seasons, and permafrost melt.

Land, Sea, Air, and Space

NASA's analysis incorporates surface temperature measurements from more than 26,000 weather stations and thousands of ship- and buoy-based observations of sea surface temperatures. These raw measurements are analyzed using an algorithm that considers the varied spacing of temperature stations around the globe and urban heating effects that could skew the conclusions if not taken into account. The result of these calculations is an estimate of the global average temperature difference from a baseline period of 1951 to 1980.

NASA measures Earth's vital signs from land, air, and space with a fleet of satellites, as well as airborne and ground-based observation campaigns. The satellite surface temperature record from the Atmospheric Infrared Sounder (AIRS) instrument aboard NASA's Aqua satellite confirms the GISTEMP results of the past seven years being the warmest on record. Satellite measurements of air temperature, sea surface temperature, and sea levels, as well as other space-based observations, also reflect a warming, changing world. The agency develops new ways to observe and study Earth's interconnected natural systems with long-term data records and computer analysis tools to better see how our planet is changing. NASA shares this unique knowledge with the global community and works with institutions in the U.S. and around the world that contribute to understanding and protecting our home planet. ■



NASA Earth Science in the News

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EDITOR'S NOTE: This column is intended to provide a sampling of NASA Earth Science topics reported by online news sources during the past few months. Please note that editorial statements, opinions, or conclusions do not necessarily reflect the positions of NASA. There may be some slight editing in places primarily to match the style used in *The Earth Observer*.

***2020 Ties for Hottest Year on Record, NASA Says**, January 14, *wsj.com*. Despite cooling ocean currents and a drop in greenhouse gas emissions, global temperatures last year were in a dead heat with those recorded in 2016. In a new climate study, NASA ranked 2020 in a tie with 2016 as the warmest year since official record-keeping began in 1880. The record-tying warmth came despite a cooling La Niña Pacific Ocean current, which tamped down global temperatures slightly in December. In a separate assessment released at the same time, the National Oceanic and Atmospheric Administration (NOAA), which relies on slightly different temperature records and methods, calculated that the globally averaged temperature last year was the second highest to date—just shy of tying the record set in 2016. "These long-term trends are very, very clear," said **Gavin Schmidt** [NASA's Goddard Institute for Space Studies—*Director*]. NASA and NOAA scientists labeled 2020 a year of extremes, driven by rising levels of greenhouse gases such as carbon dioxide and methane that trap heat in the atmosphere.

One-Third of America's Rivers have Changed Color Since 1984, January 7, *apnews.com*. America's rivers are changing color—and human activities are behind many of the shifts. A new study, published in the journal *Geophysical Research Letters*,[1] determined that one-third of the tens of thousands of mile-long (two-kilometer-long) river segments in the U.S. noticeably shifted color in satellite images obtained since 1984. That includes 11,629 mi (18,715 km) that became greener or went toward the violet end of the color spectrum, according to the study. Some river segments became more red. Only about 5% of U.S. river mileage is considered blue—a color often equated with pristine waters by the general public. About two-thirds of American rivers are yellow, which signals they have lots of soil in them. But 28% of the rivers are green, which often indicates they are choked with algae. And researchers found 2% of U.S. rivers over the years shifted from predominantly yellow to distinctly green.

[1] To read the study, visit *https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2020GL088946*.

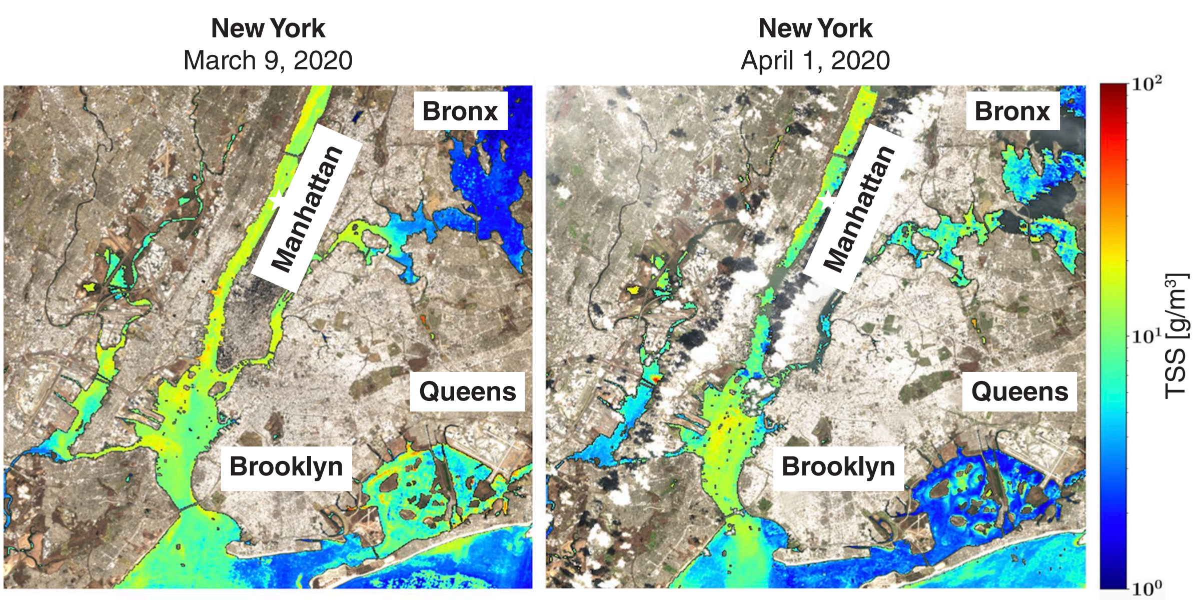

Figure. Maps of water turbidity compiled using data from NASA's Landsat 8 satellite before and during the lockdowns in New York show decreased turbidity near western Manhattan (indicated by a star). Colors represent different levels of total material suspended in the water. **Credit:** Nima Pahlevan [GSFC]

The chief causes of color changes are farm fertilizer runoff, dams, efforts to fight soil erosion, and human-caused climate change, which increases water temperature and rain-related runoff. The study looked at more than 230,000 NASA satellite images over 35 years—focusing on rivers and reservoirs—and found that much of the shift to greener rivers happened in the north and west, while the yellowing occurred more in the east and around the Mississippi River. The study also found some rivers change colors naturally with the seasons.

***Global Land Ecosystems Progressively Losing Their Ability to Absorb CO_2**, December 20, *weather.com*. Researchers identified an unsettling trend in the battle against climate change. As levels of carbon dioxide (CO_2) in the atmosphere increase, a new study shows that 86% of global land ecosystems are becoming progressively less efficient at absorbing this greenhouse gas. Because CO_2 is a main "ingredient" that plants need to grow, elevated concentrations of it cause an increase in photosynthesis, and consequently, plant growth—a phenomenon aptly referred to as the CO_2 fertilization effect (CFE). CFE is considered a key factor in the response of vegetation to rising atmospheric CO_2 as well as an important mechanism for removing this potent greenhouse gas from our atmosphere—but that may be changing. For a new study published in the journal *Science*,[2] researchers analyzed multiple field, satellite-derived, and model-based datasets to better understand what effect increasing levels of CO_2 may be having on CFE. Their findings have important implications for the roles plants can be expected to play in offsetting climate change in the years to come. "In this study, by analyzing the long-term data from remote sensing and state-of-the-art land-surface models, we have found that since 1982, the global average CFE has decreased steadily from 21% to 12% per 100 ppm of CO_2 in the atmosphere," said study author **Ben Poulter** [NASA's Goddard Space Flight Center (GSFC)]. "In other words, terrestrial ecosystems are becoming less reliable as a temporary climate change mitigator," Poulter added. Without this feedback between photosynthesis and elevated atmospheric CO_2, the researchers said climate change would occur at a much more rapid rate.

[2] The study can be viewed at *science.sciencemag.org/content/370/6522/1295.full.*

Researchers Explore COVID-19's Environmental Impact, December 7, *spacenews.com*. Researchers continue to explore the COVID-19 pandemic's impact on Earth's environment and consider implications for public policy. That was one of the takeaways of the virtual American Geophysical Union Fall Meeting, which featured dozens of presentations and posters from researchers drawing on satellite imagery and numerical data to reveal changes in deforestation, snowpack reflectivity, water quality, atmospheric aerosols, and many other indicators of environmental health. **Nima Pahlevan** [GSFC] shared ongoing research to detect water-quality changes with Landsat 8 and Sentinel-2 data products [see **Figure** on page 33]. When New York instituted a stay-at-home order, Pahlevan and his GSFC colleagues noted a significant drop in sewage discharge into the rivers around Manhattan, which they were able to detect from space. "We're still working on further localizing our analysis in Europe as well as in the San Francisco Bay Area to see how exactly COVID-19 has been impacting the surface water-quality conditions," Pahlevan said. Once researchers figure out how the pandemic-driven pause in some types of human activity have affected the environment, they can better forecast the impact of future pandemics or policy changes. "We're very interested in learning how an aquatic ecosystem would respond to lower pollution levels," Pahlevan said. It would be interesting to see the impact of lower pollution levels on fisheries and on the near-shore environment, he added.

** See News article in this issue for more details*

*Interested in getting your research out to the general public, educators, and the scientific community? Please contact **Ellen Gray** on NASA's Earth Science News Team at* ellen.t.gray@nasa.gov *and let her know of upcoming journal articles, new satellite images, or conference presentations that you think would be of interest to the readership of* **The Earth Observer**.

Earth Science Meeting and Workshop Calendar

NASA Community

NASA Community events will be updated in our next issue.

Global Science Community

April 19–30, 2021
EGU General Assembly, *virtual*
https://www.egu21.eu

August 2021
AOGS 18th Annual Meeting, *virtual*
https://www.asiaoceania.org/aogs2021/public.asp?page=home.html

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